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PAPER

Enhancing Astronomy Skills: The Role of Mobile Augmented Reality in Vietnamese Middle Schools

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ABSTRACT

This study aims to assess the impact of mobile augmented reality (AR) applications on the astronomy competencies of middle school students in Vietnam, addressing the gap in practical educational mobile applications within science, technology, engineering, and mathematics (STEM) fields. Employing a quasi-experimental design, the study involved 438 sixth graders from four middle schools in Central Vietnam over eight weeks. The experimental group utilized AR applications, while the control group received conventional textbook instruction. Astronomy competencies were evaluated through pre- and post-tests, employing self-developed questionnaires based on standardized assessments. The results indicated that students in the AR group outperformed their counterparts in the control group across key competencies, including celestial motion, spatial orientation, and conceptual understanding. Notably, analysis of spatial learning revealed that female students in the AR group performed better than their male peers. Interviews with participating students suggested that AR applications enhanced interactions and facilitated a better understanding of abstract concepts, although some technical issues were reported. These findings highlight the potential of mobile AR to improve short-term learning outcomes and suggest its role in narrowing gender gaps in STEM education. Future research should investigate the long-term effects of AR on learners and explore its application across diverse learning environments while considering infrastructural and socio-cultural constraints.

KEYWORDS

augmented reality (AR), astronomy education, middle school students, visualization, learning outcomes

1 INTRODUCTION

The development of information and communications technology (ICT) was one of the most significant milestones that have revolutionized education through constructive processes that improve learners' interaction and performance [1]. Among these emerging technologies, augmented reality (AR) stands out for its ability to enable

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real-life context and add layers of digital content [2] [3]. In science education, where ideas that are hard to understand and explain often challenge students, AR has created a great opportunity to close the gap between knowledge and comprehension [4] [5] [6].

Augmented reality technology is particularly significant in the context of developing countries like Vietnam, where it can address specific challenges in understanding complex scientific concepts. By providing immersive and interactive experiences, AR can help overcome limitations in traditional teaching methods, especially in science, technology, engineering, and mathematics (STEM) education [7]. For instance, recent studies have shown AR's potential in enhancing occupational health and safety education [8], revolutionizing CNC lathe education [9], and improving understanding of engineering mechanics [10] [11].

Nevertheless, the integration of AR in developing countries like Vietnam faces several main challenges. Under their process of digital transformation of education, Vietnam has been paying more attention to the sectors of STEM. The most recent educational reforms have shifted focus to enhancing student competencies, particularly in STEM disciplines, due to today's demand for skilled technical personnel [12]. However, Vietnamese education still encounters significant obstacles: Firstly, there is a lack of resources, such as restricted access to advanced technology, particularly in rural areas; secondly, the educational system promotes a teacher-directed approach that reduces students' independence and creativity [13]. These challenges are most prominent in STEM education, where students need help understanding abstract scientific concepts and applying theoretical concepts to solve complicated real-life problems [14].

Moreover, gender distributions within STEM disciplines remain problematic, as female students are less likely to be enrolled, and their achievements in spatial and computational skills and tasks are lower [15]. Based on these challenges, AR technology appears particularly suitable for improving STEM education in Vietnam, especially in astronomy, which requires symbolism, visualization, and spatial abilities.

Astronomy was chosen as the subject area for this study due to its relevance to broader educational reforms in Vietnam and its inherent challenges in visualization and spatial reasoning. AR's capability to generate various forms of complex animated graphics can significantly improve students' study of astronomical objects and events, such as the motion of planets and interactions. Furthermore, as it has been established that AR can capture students' participatory attention by offering unique practical lessons, it aligns with the changes in Vietnam's educational systems that aim at reducing overreliance on passive, bookish lessons.

Research questions

Based on these considerations, the purpose of this study is to examine the impact that AR learning has on enhancing competencies in astronomy compared with conventional textual-based teaching. Additionally, this study aims to investigate whether there is a gap in the results depending on the student's gender in the use of AR in learning. The following research questions guide this study:

1. To what extent does the utilization of mobile AR applications enhance the knowledge of astronomy among middle school students compared to other methods, such as using textbooks?

   This question seeks to determine the overall effectiveness of AR applications in enhancing students' astronomy knowledge, focusing on three key competencies: celestial motion, spatial awareness, and conceptual knowledge.
2. To what extent does the integration of AR technology impact students' achievement of celestial motion, spatial awareness, and conceptual knowledge in astronomy?

This question will determine if AR technology, in particular, helps enhance the above pertinent areas of astronomy education by improving the visualization and understanding of abstract astronomical concepts.

3. To what extent are there differences in learning achievements between male and female students, especially in spatial learning, when using AR applications in astronomy?

   Here, we pay attention to interpreting significant gender-based differences in how male and female students benefit from AR, whereby earlier research postulates that spatial awareness remains challenging for females [16]. We will analyze these differences to understand how AR technology can contribute to gender equality in STEM education, including spatial intelligence.

   This study contributes to the growing body of literature on AR in education, particularly in the context of developing countries. By focusing on astronomy education in Vietnamese middle schools, we aim to provide insights into AR's effectiveness in enhancing STEM education in resource-constrained environments and its potential to address gender disparities in STEM fields.

2 LITERATURE REVIEW

2.1 Theoretical foundations of AR in education

The application of AR in educational scenarios is based on several cognitive and learning theories. In this theoretical framework, embodied cognition suggests that cognitive processes are inherently linked to our physical engagement with the world or environment (a premise supported by AR, as it gives learners an interactive and experiential way to learn) [17], [18]. This theory posits that using AR to learn may be particularly effective in subjects relying on abstract visualization (e.g., astronomy) by helping students acquire information through a physical representation, positively influencing understanding and retention [19]. In addition, AR is supported by cognitive load theory (CLT), which states that digital technology can control how information and data are provided to a learner in an organized layout [20], reducing extraneous cognitive load so that learners focus on relevant material. AR applications designed in compliance with CLT can contribute to the efficient use of cognitive resources for students, which is essential, particularly within the areas of complex scientific subjects such as astronomy [21].

Although these theories give a robust premise for the utilization of AR in education, to date, little research relates this means with an end (methods) or outcomes. The theoretical constructs underpinning learning from an AR have been explicitly referred to in this study within the design of AR applications so that they function not just as presentation platforms for celestial models but also as minimizing cognitive load exposure through well-structured segments of information. Explicitly grounding these theories within an explicit methodology of quasi-experimentation allows us to design our AR applications to improve students' spatial and conceptual understanding while not overtaxing their mental faculties.

2.2 AR in science education

Augmented reality in science education has brought about impressive changes in virtually all the areas of knowledge. For example, Abdinejad et al. [22] in chemistry also described how it would enable students to visualize molecular structures or models, and they also did. That capability was illustrated when Weng et al. [23] used it to trace anatomy and ecosystems. Especially in physics, Radu and Schneider [24] show that the use of AR increases the tangibility of content in subject-matter located in rather abstract contexts such as electromagnetic fields. These studies show the potential of AR to help make complex scientific concepts more comprehensible to students by letting them interact with 3D models and simulations.

However, these studies rarely deal directly with AR technology's challenges, especially in the constraints of the low resource contexts. Much of the focus lies on how quickly students learn, with intermittent focus on long-term retention. In addition, most of the studies are conducted in higher learning institutions, which makes the students more likely to own some devices and may be educated more than those in the lower classes. This creates a research gap for evaluating the impact of AR in middle school education, especially in developing countries such as Vietnam. The present study contributes to filling this gap by investigating the effects of mobile AR apps on middle-grade students' achievements and short-term knowledge retention while specifying further directions for long-term knowledge preservation research.

2.3 AR in astronomy education

Teaching and learning astronomy are not accessible because most of the concepts in this field are related to spatial reasoning and abstract concepts. Some of the studies carried out at an initial stage of AR implementation are by Shelton and Hedley [25], who found a boost in the ability of students to reason spatially while learning Earth-Sun relations through AR. Herfana et al.'s [26] and Fleck and Simon [27] more recent investigations support the notion that using AR increases students' content knowledge in astronomy, particularly motions of celestial bodies and the moon's phases. These studies give substantial evidence of the benefits of AR in the improvement of the learners' spatial skills. In contrast, these benefits relate to the different learning environments and the learners' long-term academic performance. However, most of these studies need to explore the connection more elaborately.

Also, according to the available literature, more research is needed on the effects of AR on gender-differentiated outcomes in astronomy learning. Hou and Wang [28] imply that female students may derive more advantages in spatial skills when they perform AR tasks, while the existing gender differences studies concerning AR-mediated learning are somewhat mixed. Our study further continues this line of research because it not only focuses on the gender differences in learning outcomes but also investigates whether AR technology can reduce gender gaps in STEM, particularly in spatial skills.

2.4 Recent studies on AR in education

Research carried out in the last few years supports the growing possibility of AR use in learning, especially regarding enhancing learners' participation and understanding in diverse learning areas. This work by Antoniadi [18] demonstrated how the use of AR enhances the knowledge of plant structures in primary school-going learners, thus revealing the flexibility of AR for young learners. Increasing student engagement and attention level, Campos-Pajuelo et al. [29] proved that AR can help elementary students remember chemical elements. These works indicate that AR could be utilized at many levels and in all learning disciplines.

Similarly, in regards to astronomy education, using the app proposed by Beltozar-Clemente et al. [30], the authors found that the application significantly enhanced the learning process of students as it relates to astronomy education and further affirms the belief that AR facilitates learning as a result of the visual interaction. These recent researches, mainly conducted in Western countries, contribute to the previous findings about the effectiveness of AR in various learning environments. However, they also recognized the necessity of continuing the research in the Vietnamese context.

Our study extends such research, concentrating on Vietnamese middle school students primarily underrepresented in AR investigations. Hence, our attempt to use AR technology in this sense is also to advance knowledge about AR's utility in education, especially in developing countries with little technological base.

2.5 Addressing limitations in prior research

With many existing studies discussing the benefits of AR in education, AR still has several drawbacks that can be noted. However, some beneficial studies present in current literature, overlook the long-term impacts of learning facilitated by AR technology [31–34]. Further, previous literature needs to consider infrastructural and socio-cultural factors that may hinder the successful integration of AR technology in learning environments, especially in developing countries such as Vietnam.

Of course, our work helps to overcome these limitations by examining both the short- and potential long-term effects of AR on astronomy competencies. We also explain how AR can be best deployed in Vietnamese middle schools and under constraints such as teacher training, available support technology, and the readiness of students. Therefore, this study intends to offer a broader picture regarding AR's outcomes in education, which might be helpful for both policy and practice in the case of Vietnam and other comparable educational systems.

3 METHODOLOGY

3.1 Research design

In this study, a quasi-experimental design was used to determine the effects of mobile AR applications on students' astronomy competencies in the studied middle schools in Vietnam. Aims included comparing an experimental group, using applications with AR, and a control group using standard texts. The use of a quasi-experimental design enabled the examination of the systematic differences between groups while controlling other variables, such as academic ability and gender, when the students joined the class.

3.2 Sample description

The participants in this study were 438 students in grade six aged 11 to 12 years old (M = 11.6, SD = 0.4) from four middle schools in the central region of Vietnam. The sample used in this case comprised a stratified random sampling technique to make the results a cross-section of geographic and social standards—specifically, 50.2% of the sample was from the urban areas, while 40.8% was from the rural areas.

This process of stratification presupposed the possibility to analyze the differences in the efficiency of the ARs for the students from different conditions. According to their socio-economic status (SES), 25.1% of the students belonged to high SES status, while 49.3% were from medium SES families and 25.6% were from low SES families, which indicated that the economic background of the Vietnam students is quite heterogeneous. Based on a pre-intervention survey, the student's previous experience in AR technology was considered very low, as less than half of the students mentioned that they used the technology for less than 10%. Such limited exposure made it possible to ensure that most of the students began the study at almost the same level of awareness of AR technology. Table 1 presents the demographic characteristics of the participants.

Table 1. Participant demographics

Demographic Characteristics of Participants	Experimental Group (n = 219)	Control Group (n = 219)	Total (N = 438)
Gender			
– Female (n, %)	112 (51.1%)	112 (51.1%)	224 (51.1%)
– Male (n, %)	107 (48.9%)	107 (48.9%)	214 (48.9%)
Location			
– Urban (n, %)	110 (50.2%)	110 (50.2%)	220 (50.2%)
– Rural (n, %)	109 (49.8%)	109 (49.8%)	218 (49.8%)
Socioeconomic Status			
– High (n, %)	55 (25.1%)	55 (25.1%)	110 (25.1%)
– Medium (n, %)	108 (49.3%)	108 (49.3%)	216 (49.3%)
– Low (n, %)	56 (25.6%)	56 (25.6%)	112 (25.6%)
Mean Age (years) ± SD	11.6 ± 0.4	11.6 ± 0.4	11.6 ± 0.4

3.3 Instruments

In order to assess the level of the astronomy competencies of the students, the astronomy competency test (ACT) was designed as a 40-item multiple-choice test. The ACT covers three main domains: understanding of celestial motion (14 items), spatial awareness in astronomical contexts (13 items), and conceptual knowledge of astronomy (13 items). While the test's internal consistency was high (Cronbach's $\alpha = 0.89$), additional steps were taken to ensure the test's validity.

Consequently, the content validity of the ACT was determined using five astronomy educators and two psychometricians. Each expert evaluates the orientation and clarity of the test items and reflects on the learning outcomes of the Vietnamese astronomy curriculum. Since then, the reviewer's comments have informed some of the modifications made to some test items to enhance clarity and applicability. Also, a pilot study of 120 students was carried out to validate the ACT. Some information collected in the pilot study was analyzed using item response theory (IRT) to assess the items' difficulty and efficiency. For this reason, the final version of the test had an acceptable goodness of fit to the three-factor model: CFA test, CFI = 0.95 with the RMSEA of 0.05, and it was evidenced that the test effectively captured the intended constructs.

The student perception questionnaire (SPQ) was a 20-item standardized self-completed survey measuring students' perceptions of learning with AR. The SPQ incorporated items relating to perceived usefulness, perceived ease of use, and perceived learning. Expert review was also conducted on this instrument and pilot testing, and further analysis yielded a high internal reliability of $\alpha = 0.91$.

In addition, through a series of semi-structured interviews, qualitative data were obtained from a purposive sample of 40 students, 20 of whom were in the AR group and the other 20 in the control group. The questions were designed so the students could express their learning experience, difficulties with the teaching methods, and the perceived advantages of AR application. These interviews revealed the students extensive experiences, and the present paper employs thematic analysis to strengthen the qualitative findings of these interviews.

3.4 Data collection procedures

Quantitative data. Pre-test: All participants completed the ACT one week before the intervention.

Intervention: The eight-week intervention period followed, with the experimental group using the AR application and the control group receiving traditional instruction.

Post-test: The ACT was administered again to all participants one week after the intervention.

SPQ: The experimental group completed the SPQ immediately after the post-test.

Qualitative data. Semi-structured interviews were conducted with a subset of 40 students (20 from each group) selected through maximum variation sampling to ensure diverse perspectives. Interviews lasted approximately 30 minutes each and were audio-recorded for later transcription and analysis.

3.5 Data analysis

Quantitative analysis. The quantitative data were analyzed with the help of IBM SPSS statistics 26. Independent t-tests, as well as analysis of covariance (ANCOVA) tests, were carried out to compare the results of the experimental and control groups. In order to compare the effects of the AR intervention on the astronomy competencies and control for pre-test scores, ANCOVA was used to compare the groups' performance, thus controlling for the initial differences. This method was used to estimate the intervention effects more accurately, as all developmental changes were adjusted by the differences in the student's initial knowledge state.

The rationale for using independent t-tests was highlighted where the results of current competency areas such as celestial motion, spatial awareness, and conceptual knowledge would be compared between experimental and control groups to make meaning out of learnings as to whether there was an outperformance of the experimental group. This enabled the size of these differences to be determined with the help of the so-called Cohen's d coefficients, where the higher values pointed to a more substantial impact of the studied AR intervention. The analysis was further taken a notch higher and considered gender through a two-way ANCOVA with gender and the type of intervention as the two independent variables. This method enabled the researcher to investigate the effect of gender, whereby the male and female students' outcomes with the AR application were compared.

Qualitative analysis. Qualitative data collected from the semi-structured interviews were analyzed using thematic analysis. In line with the six-step approach recommended by Braun and Clarke [35], the interviews were transcribed and subjected to coding to ascertain patterns about AR or conventional teaching from the viewpoint of the students. This process provided a better understanding of how AR applications affected students' engagement, spatial skills, and learning experience, where qualitative findings complemented the quantitative data.

4 RESULTS

4.1 Quantitative findings

Impact of AR on astronomy competencies. A one-way ANCOVA was conducted to determine the effect of the AR intervention on overall astronomy competencies, controlling for pre-test scores. The results revealed a significant main effect of the intervention, $F(1, 435) = 187.42$, $p < .001$, $\eta^2 = 0.301$. The AR group ($M = 8.1$, $SD = 1.2$) significantly outperformed the control group ($M = 6.6$, $SD = 1.4$), with a large effect size (Cohen's $d = 1.14$). The findings demonstrate that AR applications have a substantial impact on students' understanding of astronomy, especially in complex areas such as celestial motion and spatial awareness.

Table 2. Comparison of astronomy competency domains between AR and control groups

Domain	AR Group (n = 219)	Control Group (n = 219)	F	p	η^2	Cohen's d [95% CI]
Celestial Motion	8.2 (1.3)	6.7 (1.5)	156.31	<.001	0.264	1.05 [0.86, 1.24]
Spatial Awareness	7.8 (1.2)	6.3 (1.4)	178.64	<.001	0.291	1.15 [0.96, 1.34]
Conceptual Knowledge	8.0 (1.1)	6.5 (1.3)	192.75	<.001	0.307	1.24 [1.05, 1.43]

Table 2 summarizes the effect sizes for each competency domain, showing that the AR group consistently outperformed the control group across all areas. The largest effect size was observed for conceptual knowledge (Cohen's $d = 1.24$), indicating a particularly strong impact of AR on students' grasp of astronomical concepts. These findings suggest that AR applications significantly enhance students' abilities to understand and engage with abstract and spatially complex material.

Gender differences in AR effectiveness. A two-way ANCOVA was conducted to explore the interaction between gender and intervention type on astronomy competencies, controlling for pre-test scores. Results indicated a significant main effect of intervention ($F(1, 433) = 183.56$, $p < .001$, $\eta^2 = 0.298$), a small but significant main effect of gender ($F(1, 433) = 6.78$, $p = .010$, $\eta^2 = 0.015$), and a significant interaction between gender and intervention type ($F(1, 433) = 4.92$, $p = .027$, $\eta^2 = 0.011$). Post-hoc analyses with Bonferroni correction showed that female students in the AR group ($M = 8.5$, $SD = 1.1$) demonstrated significantly greater improvement in spatial awareness compared to their male counterparts ($M = 8.0$, $SD = 1.2$), $t(217) = 3.24$, $p = .001$, Cohen's $d = 0.44$. Table 3 presents the gender-specific results for each astronomy competency domain in the AR group:

Table 3. Gender comparison of astronomy competency domains in AR group

Domain	Females (n = 112)	Males (n = 107)	t	p	Cohen's d [95% CI]
Celestial Motion	8.7 (1.1)	8.3 (1.2)	2.54	.012	0.35 [0.08, 0.62]
Spatial Awareness	8.6 (1.0)	8.1 (1.1)	3.45	<.001	0.47 [0.20, 0.74]
Conceptual Knowledge	8.4 (1.2)	7.9 (1.3)	2.88	.004	0.40 [0.13, 0.67]

These gender-specific results reveal that AR applications not only improve overall astronomy competencies but also play a role in reducing gender disparities in spatial reasoning. Female students, who traditionally underperform in spatial tasks, seem to benefit more from AR's interactive, embodied learning environment. This has important implications for addressing gender gaps in STEM education, particularly in subjects requiring strong spatial reasoning skills.

Student perceptions of AR learning experience. Analysis of the SPQ revealed high levels of engagement and perceived learning benefits among AR group participants. The mean overall satisfaction score was 4.2 out of 5 (SD = 0.6). Table 4 presents the mean scores for key dimensions of the AR learning experience:

Table 4. Student perceptions of AR learning experience

Dimension	Mean (SD)
Engagement	4.5 (0.5)
Ease of Use	4.0 (0.7)
Perceived Learning Benefits	4.3 (0.6)
Motivation to Learn Astronomy	4.4 (0.5)

While the overall satisfaction and the scores are higher in other vital areas such as engagement, perceived learning benefits, and motivation, it can, therefore, be concluded that AR has considerable potential for enhancing the students' learning experience in astronomy. It also assists in explaining complex subjects and makes learning exciting and fun, which is crucial because students tend to view topics such as astronomy as complicated.

4.2 Qualitative findings

Thematic analysis of the semi-structured interviews revealed four main themes:

1. Enhanced visualization and spatial understanding: Students consistently reported that AR helped them better visualize astronomical concepts. One student noted, "Seeing the planets move in 3D made it much easier to understand their orbits" (student 17, female). This aligns with the quantitative findings, where spatial awareness showed significant improvement in the AR group.
2. Increased engagement and motivation: Many students expressed heightened interest in astronomy due to the AR experience. A male student stated, "I look forward to astronomy class now. It's like exploring space in real life" (student 8, Male). These qualitative insights suggest that AR not only improves academic outcomes but also fosters a more engaging and enjoyable learning experience, which could have long-term benefits for student motivation in STEM fields.

3. Collaborative learning opportunities: The AR application facilitated peer-to-peer learning. A female student observed, "We often gathered to explore the AR models together, which led to interesting discussions" (student 23, female). This indicates that AR technology can facilitate collaborative learning environments, an important aspect of modern educational practices that focus on teamwork and communication skills.
4. Technical challenges and learning curve: Some students reported initial difficulties in using the AR application. "It took some time to get used to the controls, but once I did, it was really fun" (student 12, male). This highlights the importance of adequate support and training for both students and teachers to maximize the potential of AR in educational settings.

The findings of this investigation support the hypothesis, necessarily stating that AR applications improve students' astronomy literacy profiles, more so in the spatial understanding and the conceptual knowledge domain. These implications suggest the direction for implementing AR technology in learning, particularly in disciplines concerning elementary and complicated visuals. AR thus complements conventional teaching methods for students by offering them hands-on experience by interacting with models and simulation.

From a practical point of view, since AR was found to enhance gender-specific outcomes, it is believed that AR can play a significant role in eliminating gender differences in the enrollment of STEM courses. This means that the enhancement of spatial ability by female students will lead to the closing of the gap by students in areas where this skill is essential in fields such as the use of AR. For educators and policymakers, this underlines the need to use AR as an additional tool during teaching and learning processes and as one of the priorities for improving STEM education.

In addition, the positive response from students for the engagement and motivation scale confirms that AR could have great potential to help students remain interested in STEM subjects, a factor that most education systems struggle to tackle. However, the difficulty level encountered during technical practical by some students has revealed that adequate infrastructural support is required. For the goal of AR to be achieved in its entirety, there is a need to make more investments in teacher training, technology devices, and easier-to-use AR applications.

5 DISCUSSIONS

This study investigated the impact of mobile AR applications on the astronomy competencies of Vietnamese middle school students. The results demonstrate that AR significantly enhances students' understanding of celestial motion, spatial awareness, and conceptual knowledge, with notable improvements among female students in spatial reasoning. First, these results provide several insights into the practice of education with the following recommendations:

5.1 Implications for practice

The research implications detailed in this paper provide several guidelines for teachers and policymakers who wish to import AR into classrooms, especially in STEM subjects such as astronomy. AR's first application helps illustrate concepts that are hard to describe and explain in conventional lecturing and tutoring. Thus, by enabling students to use visual manipulations to rotate or zoom into celestial body models and then watch planetary movements in real-time, AR can bring practical practice from theoretical knowledge. It is recommended that educators should include the use of AR applications as one of the most critical components of the teaching-learning process, that is, teaching and learning methodologies, particularly in areas of teaching-learning where students are required to understand spatial orientation and shapes or even work on abstract images.

Besides, the gender-specific results suggest that AR may promote the equal performance of male and female students in STEM, especially regarding spatial skills, to which females are more vulnerable. Educators can use AR to enhance teaching-learning processes to accommodate students with different learning abilities, closing the gap in STEM courses based on the student's gender. Teachers should also be educated on how to use AR and how to benefit from AR applications based on teamwork and inter-student communications as a result of the latter study.

Lastly, educators should also pay attention to other aspects related to integrating AR technologies in education, such as the technical aspects needed to implement the technologies. Since some students complained of technical difficulties, schools must provide the proper hardware, appropriate internet connection, and necessary training for teachers to utilize AR applications in learning institutions properly. Teachers should possess the required competencies to facilitate the students in AR-based activities, handle the problems observed during their implementation, and incorporate AR content with other teaching resources. Last of all, the motivational benefits realized in the current study imply that AR could go a long way in enhancing students' interest in STEM subjects.

That way, AR might help solve the problem of dwindling motivation among learners, resulting in low enrollment in such courses. Some of the suggested goals for AR implementation in teaching and learning processes are as follows: Teachers are welcome to discover numerous applications of AR addressing different ages and subject backgrounds to maintain the students' interest and ensure the long-term perspective toward STEM fields.

5.2 Limitations

However, some limitations must be considered while discussing this study's findings. Self-selection is another possible limitation that may impact the selected sample. The participants were divided into experimental and control groups using random assignment. However, the level of students' intrinsic motivation or interest in technology might influence the use of AR and the results obtained. Subsequent research should eliminate such bias using random assignment methodologies in various educational contexts and with more prominent, representative participants. A third limitation is that the intervention was carried out for only eight weeks, so that it would be ineffective. Another weakness of the study is that it improved the percentage of students acquiring astronomy competencies in the short term. However, the long-term status still needs to be discovered. Further research will also require long-term research to establish the durability of using AR in learning and the extent to which students could retain the information. It has also been suggested that carrying out such studies can assess the effect of the use of AR on students' future academic choices, especially in STEM careers. Also, the study was conducted on a restricted subject area of science, astronomy, and thus, the conclusions derived cannot be generalized to other branches of science. AR has been tested in chemistry and physics education. Therefore, the present studies deserve more research on their application in other STEM fields such as biology or environmental sciences. This is an area of research in which future studies must explore astronomy and, if similar gains are realizable in other topics, whether specific AR interventions are more beneficial in some subject areas than others. Also, the research presumed equal availability of resources to the participants, a situation that rarely occurs in many classes, especially those from rural backgrounds. Despite this study adopting a matched-pair design to minimize differences in socioeconomic status, this or that differences in the sophistication of technologies could have skewed the results. Subsequent studies should establish if factors such as the availability of gadgets, internet connection, and the users' understanding of computers affect AR applications and performance. Exploring low-cost or offline AR solutions could also help make AR technology more accessible to students in developing countries.

5.3 Future research directions

Some of the main areas for future research are discerned from the present study. First, as has been mentioned above, using this type of research makes it possible to investigate the impact of AR on learning outcomes in the long term. In particular, subsequent research should examine short-term changes in students' astronomy content knowledge, long-term academic achievement, and enhanced understanding of astronomical concepts. Furthermore, the effectiveness of AR in improving the students' interest in STEM careers can be determined, and the suitability of AR in nurturing future generations of STEM professionals can be identified.

Second, the cross-sectional survey is necessary to establish the generality of these findings. Although this study was mainly conducted in Vietnam, there are still many research gaps for investors, learners, educators, and policymakers, especially regarding how and to what extent AR performs in various education systems and cultural settings. *Sidenote:* Comparative analyses of the countries where the transition toward technology integration in education is in a different phase can help understand how AR can be effectively used when addressing the needs of various students.

Third, content expansion for future research should consider the customization of the AR learning experience. Integrating artificial intelligence (AI) into AR applications might make learning environments sensitive to students' needs and preferences. Personalized AR could increase the level of students' interest and play the role of effective individualization of teaching methods for students with different learning profiles. Such research could probably examine how best the use of AI in improving AR efficiency impacts students' achievement.

Lastly, the study should explore the interaction of AR with other related technologies such as virtual reality (VR), machine learning, and gamification. When AR is integrated with these, it increases the possibilities of a highly engaging and interactive education environment for science learning. Research focusing on the synergy of multiple technologies in a learning environment may reveal new possibilities for increasing students' interest and learning effectiveness.

6 CONCLUSION

This study offers significant empirical substantiation of mobile AR applications in developing Vietnamese middle-school students' astronomy competencies. In the quasi-experimental study, we showed that the learning gains in students using AR were significantly higher than in the control group regarding celestial motion, spatial orientation, or conceptual understanding. Moreover, the gains evidenced only for gender suggest that STEM education for girls and boys respectably, AR has a great potential for decreasing gender gaps in STEM learning. These results support the emerging literature on AR and suggest that it can be a valuable approach for remedying the difficulties of teaching conceptual content, as inherent to the sciences.

Apart from implications for the present study conducted in educational settings, it has implications for educational policy and practice in Vietnam. With the focus nowadays on enhancing digital learning in education, AR is one of the viable ways to address the issues of achievement gaps, students' motivation, and thinking skills, which are all important in preparing students for global society. Through the ability to simulate a student's experience with content by using 3D models in AR, the opportunity arises for this gap to be closer or eliminated, a problem that has been the bane of Vietnamese education systems in the past. Besides, proving that integrating AR into a subject such as aeronautics was possible, and such a complex subject requires high spatial IQ, shows how reform in STEM education across the curriculum is achievable.

Consequently, there is a high probability that AR technology will be receptive to determining the prospects of reforming the educational system in Vietnam. Given the trends towards growing international competition and the necessity of integrating advanced technologies into people's lives, the results support the choice of innovative educational technologies to improve learners' performance. AR used in the classroom could help transition from conventional modes of educator-focused delivery to learner-engaged models. This shift is especially essential in Vietnam due to the issues that STEM education is experiencing, including poor infrastructure, memorization, and gender gaps.

The study also addresses the issue of the distribution of technology and the inequality in making learning augmented through AR, which is also a consideration as this kind of learning should be accessible to all students, especially those from different economic backgrounds. As Vietnam is consistent in its digital transition journey, policy measures that involve investment in EdTech, teacher professional development, and information communication technology are essential. From the above argument, it is pretty clear that there is a need for a proper framework that provides guidelines for integrating AR in classroom settings to be successful. Such devices and software are needed for the implementation of AR and the necessary support for the teachers and school.

Based on the result of this study, it is concretely benefiting educators and policymakers to act immediately to undertake and practice AR technologies in learning environments more actively. For educators, using AR in their teaching area is a great chance to offer the children engaging and exciting lessons that will help them think critically and solve problems. Teachers should endeavor to acquire professional development in using AR tools and how they can apply them in most areas of their work, not necessarily limited to the STEM disciplines. In doing so, educators can thus equip learners with the aptitude that will enable them to succeed in the face of the growing trends in computerization and globalization in the future.

Besides, the policy and practice analysis highlighted the importance of further investigation of AR's impact on education outcomes. Subsequent research should evaluate the effects of AR in both short-term cumulative comprehension and learners' enhanced interest in STEM disciplines in the long run. Further research can be done in other fields since learning is not limited to AR but includes other technologies, such as VR and AI, to enhance learning. Through such processes of enhancement and broadening the scope of application of AR, educators and researchers will be able to reveal the entire potential of technology to revolutionize learning processes for all learners.

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