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Research Article

Student views on instruction supported by mobile augmented reality

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ABSTRACT

This study investigated middle school students' perceptions of mobile augmented reality (MAR)-supported instruction in the *solar system* unit. Designed as a qualitative case study, the research involved 22 sixth-grade students who completed pre- and post-implementation opinion forms. Data were analyzed through inductive content analysis, supported by expert validation and intercoder reliability procedures. Findings indicated that students expected MAR to enhance visualization, motivation, and enjoyment in learning. Following the four-week instructional process, most of these expectations (86%) were fulfilled. Students reported that MAR facilitated a clearer understanding of planetary features and fostered active participation, while a small number expressed negative views due to challenges in technology use and group-based activities. These findings align with previous research emphasizing MAR's cognitive and affective benefits, while also highlighting implementation challenges such as technical constraints and classroom management issues. Overall, the study demonstrates that MAR can enrich science education by integrating conceptual learning with engagement and motivation. Situated within the framework of the 2018 and 2024 Turkish science curricula, the findings illustrate how MAR aligns with national priorities for digital transformation while revealing infrastructural constraints in real classroom contexts. The study contributes to the growing body of literature on augmented reality in education by presenting both the opportunities and limitations of MAR integration and by offering practical insights into educators and researchers seeking to embed emerging technologies into science instruction.

Keywords: mobile augmented reality, science education, student perceptions, technology-enhanced learning

INTRODUCTION

Today's students are described by a variety of terms such as 21st century learners, Generation Z, the virtual generation (V generation), Screenagers, the Internet generation, and digital natives (Adıgüzel et al., 2014; Vogel, 2015). Prensky (2001) defines digital natives as the generation born into modern technology and the culture surrounding it, while McCrindle (2012) uses the term Generation Z for individuals born after 1995. These individuals represent the younger generation in society with the highest tendency to use technology. In this context, Generation Z demonstrates behavioral patterns and life habits that differ from previous generations. Among these differences, the most notable is their use of technology. Their early exposure to technological tools and devices also differentiates their learning preferences from those of earlier generations.

Generation Z expects quick access to information and materials in digital environments. Rather than text-based content, they prefer multimedia materials that include visual and auditory elements. Furthermore, the

Internet and similar digital platforms are perceived by this generation not as virtual spaces but as extensions of real life, which makes it difficult for them to distinguish between digital and physical life (Günüç, 2017).

In today's era, often referred to as the mobile age, the global increase in the use of mobile devices and the functional diversity of these devices have accelerated the integration of mobile technologies into learning processes (Karapınar & Balım, 2019). Mobile learning is being increasingly integrated into higher education processes by many universities around the world (Nordin et al., 2010). For example, under the MOBIlearn project, 24 countries–including EU member states, as well as Israel, the USA, Switzerland, and Australia–aimed to enhance learning through mobile technologies. At Makerere University (2016), the mobile application MakApp enables students to access the learning management system and follow instructional processes. Similarly, the University of Glasgow and the University Sussex have incorporated mobile learning into their instructional planning and conducted studies on its outcomes (Kalinic et al., 2011). Mobile learning is defined as a form of learning that allows access to educational content through mobile devices without constraints of time and place, supports interaction with other technologies, and enables learners to progress at their own pace (Özdamar Keskin & Kılınç, 2011). In this context, augmented reality (AR) applications implemented via mobile devices are also considered among mobile learning techniques.

Augmented Reality

AR is a technology that enables real-time interaction between real and virtual environments by overlaying virtual elements (such as visual or auditory components) onto physical objects (Azuma, 1997). Zachary et al. (1997) define AR as a platform that synchronizes 2D/3D visuals, audio, video, and GPS location data with the physical world through technological tools such as computers, tablets, and smartphones. Initially developed for military training and industrial machine assembly, this technology has gradually become widespread in various fields such as architecture, travel, advertising, tourism, commerce, engineering, and sports (Chang et al., 2010; Lee, 2012; Somyürek, 2014).

In the context of education, AR offers significant opportunities due to its ability to integrate real and virtual environments, concretize abstract concepts, and create multisensory interactions (Billinghurst et al., 2001). AR technology is effectively used in education–especially in science–for the three-dimensional representation of certain abstract concepts (e.g., magnetic fields, molecular geometry, and solar system), for enhancing information presentations in museums, for explaining theory-space relationships in mathematics, for conceptual visualizations in geography, and for developing knowledge and skills in medical education.

In addition, the literature frequently emphasizes the positive effects of AR technology, such as enhancing conceptual learning (Echeverria et al., 2012), increasing academic achievement (Fidan, 2015; Küçük, 2015), promoting knowledge retention (Perez-Lopez & Contero, 2013), boosting student interest and motivation (Chang et al., 2014), and supporting the development of spatial skills (Gün & Atasoy, 2017). In this context, possible disadvantages of AR applications–such as technological infrastructure requirements, classroom management challenges, and attention distraction–are also highlighted (Bower et al., 2014; Dunleavy & Dede, 2014).

Additionally, recent research highlights that students' prior familiarity with AR/mobile augmented reality (MAR) technologies can significantly influence their perceptions and learning outcomes (Akçayır & Akçayır, 2017). Learners with prior experience tend to adapt more easily and report higher engagement, while those with no exposure sometimes experience greater cognitive load.

Finally, studies underline the importance of cultural and educational contexts in shaping MAR adoption (Garzón & Acevedo, 2019). Factors such as technology infrastructure, teacher readiness, and curriculum alignment influence both the feasibility and the perceived benefits of MAR-based instruction, which is especially relevant in the Turkish context where resource availability varies across schools.

This study is grounded in a constructivist learning perspective, which emphasizes that learners actively construct knowledge through engagement, interaction, and reflection rather than passively receiving information. MAR applications support this perspective by enabling students to visualize abstract astronomical concepts and integrate new ideas with their prior knowledge through exploration and manipulation of 3D models (Fosnot, 2005).

The 5E (engage, explore, explain, elaborate, evaluate) instructional model, developed by the biological sciences curriculum study (Bybee et al., 2006), was deliberately chosen to structure the integration of MAR into the instructional process. The 5E model, which is grounded in constructivist learning theory, provides a systematic framework for designing inquiry-based learning environments and has been widely adopted in science and STEM education.

In this study, the 5E model guided the instructional design as follows: the engage phase activated students' curiosity and prior knowledge, the explore phase enabled hands-on interaction with MAR simulations, the explain phase facilitated collaborative sense-making, the elaborate phase extended understanding to related astronomical phenomena, and the evaluate phase allowed students to reflect on and demonstrate their learning progress.

This theoretical alignment ensured that MAR activities were not used merely as technological add-ons but were pedagogically integrated into a student-centered, inquiry-based framework.

Despite the growing interest in MAR applications in science education, the literature reveals persistent challenges, such as limited technological infrastructure, difficulties in classroom integration, and varying levels of student familiarity with digital tools (Akçayır & Akçayır, 2017; Bacca et al., 2014). These factors raise questions about how effectively MAR can support learning when implemented in real classroom contexts. In particular, there is a lack of research exploring middle school students' perceptions of MAR-supported instruction in the Turkish context, where rapid digitalization efforts coexist with resource constraints. Addressing this gap is crucial, as students' perspectives provide valuable insights into both the pedagogical opportunities and the practical limitations of MAR integration. By focusing on students' experiences, this study aims to contribute to a deeper understanding of how MAR applications can be meaningfully incorporated into science education to enhance conceptual learning, motivation, and engagement, while also identifying the contextual barriers that need to be addressed.

The aim of this study is to determine students' opinions regarding the MAR-supported instructional process. For this purpose, an instructional plan was prepared based on the learning objectives outlined in the 6^{th} grade science course curriculum. The research question of the study can be stated as follows: What are the experience-based opinions of 6^{th} grade students regarding the instructional process supported by MAR applications within the scope of the "solar system" unit? Although numerous studies have explored the effectiveness of AR in science education, much of this research has focused on achievement outcomes or system design rather than learners' lived experiences and perceptions. However, understanding students' perspectives is essential for identifying how AR is actually interpreted, appropriated, and sustained in real classroom contexts. As emphasized in recent reviews (Sattar et al., 2025; Simon et al., 2025), capturing learners' voices is critical for developing pedagogically meaningful and context-sensitive models of technology integration. Therefore, this study makes a novel contribution by examining students' first-hand experiences and perceptions of MAR-supported instruction within a public middle school setting that reflects the typical infrastructural realities and curricular context of Turkish science education.

METHOD

This study aimed to examine, in depth and within a bounded group, the impact of a science instructional process supported by MAR applications on students' perceptions and learning experiences. In this respect, the research was structured as a case study (Merriam, 2009; Yin, 2018).

A case study design was deliberately chosen because the primary goal was not to test hypotheses under controlled conditions, but to capture the authentic experiences of students in a natural classroom environment and to provide a holistic understanding of how MAR-supported instruction was implemented and perceived (Creswell, 2012). This approach was particularly appropriate since the study sought to explore real-life interactions and meaning-making processes rather than to measure the technical effectiveness of a learning medium. As Yin (2018) emphasizes, case studies are well suited for investigating educational phenomena within their natural contexts.

Participants

The study included 22 6th grade students (8 girls and 14 boys) from a public middle school in western Turkey. We adopted a purposive sampling approach, prioritizing a site with adequate infrastructure for MAR (e.g., stable Internet connectivity and access to mobile devices) so that the instructional activities could be implemented as designed. This approach ensured both contextual appropriateness (alignment with the targeted solar system unit and 5E-based lesson flow) and procedural feasibility (minimizing implementation disruptions due to infrastructure). In addition, the cohort had limited prior familiarity with MAR, which enabled us to examine first-time user perceptions in a typical public-school setting. The sample size (N = 22) corresponds to an intact classroom at the study site–appropriate for qualitative case work–and was adequate for capturing variation in student views; thematic saturation was observed before all responses were coded.

Data Collection Tools

To determine students' opinions regarding the MAR application, a pre-implementation student opinion form and a post-implementation student opinion form (**Appendix A**) were used. The pre-implementation form included four open-ended questions concerning students' prior knowledge of MAR technology, their expectations from the application, the potential contributions of the technology to the science course, and the reasons for these contributions (e.g., "What do you expect to learn with the help of MAR applications?"). The post-implementation form consisted of six open-ended questions and reflective prompts, focusing on students' overall opinions regarding MAR-supported instruction, whether the application met their expectations, and the functionality of its use in the solar system unit. In addition, students were asked about the learning outcomes achieved through this technology, their views on how AR could be used in other subject areas, and the problems encountered during the instructional process (e.g., "What difficulties did you experience while using MAR in class?"). The structure of these forms allowed the data to capture both the cognitive (e.g., conceptual understanding, visualization) and affective (e.g., motivation and engagement) dimensions of students' learning experiences.

Data Collection and Data Analysis

The instructional implementation of the study was conducted over a period of four weeks during the first semester of the 2021-2022 academic year, specifically between September and October. The application was carried out with sixth-grade students (N = 22) enrolled in a public middle school located in a city center in the western region of Turkey. The school was selected based on the adequacy of its technical infrastructure and physical conditions. A MAR-supported instructional process aligned with the 5E instructional model was implemented for the study group. To determine students' opinions regarding the instructional process, pre-implementation and post-implementation student opinion forms were used.

The data obtained from the pre- and post-implementation student opinion forms were analyzed using the content analysis method within the framework of qualitative research. Written responses provided by students were individually examined, and expressions with similar meanings were grouped under themes, adopting an inductive approach (Yıldırım & Şimşek, 2016). In this way, efforts were made to ensure the internal validity of the data.

The data analysis was conducted by the researcher and subsequently re-evaluated by a subject matter expert. The expert's findings were compared with those of the researcher, and consistency between the analyses was ensured. This process enhanced the repeatability and, consequently, the reliability of the qualitative data (Creswell, 2012). In addition, we conducted an inductive thematic content analysis in four stages to examine students' written responses:

1. Open coding: Two researchers independently reviewed all responses line by line to identify meaningful units and generate initial codes.
2. Codebook development: The codes were compared, overlapping ones were merged, and clear definitions were established for each code.
3. Theme generation: Codes were grouped into sub-themes and broader themes using axial coding to capture patterns across students' perceptions.

4. Validation and reliability: To ensure consistency, two independent researchers coded a stratified subset of 25% of the data. Intercoder reliability was calculated using Cohen's kappa (κ = 0.79), indicating substantial agreement. Any disagreements were resolved through discussion until full consensus was reached.

Additionally, to enhance trustworthiness, we maintained a detailed audit trail (code definitions, memos, and revisions) and engaged in peer debriefing sessions with an external qualitative research expert. Thematic saturation was reached when no new codes emerged after analyzing the responses of approximately 18 students.

To illustrate the coding process more clearly, for example, the student response "I liked the 3D planetary models" was initially coded as visual engagement, which later contributed to the subtheme cognitive support and ultimately became part of the broader theme enhanced visualization. Providing this layered structure ensured that codes, subthemes, and themes were consistently derived and validated.

Instructional Implementation Process

The instructional process developed in accordance with the aim of the research was first tested through a pilot study conducted with a different sample group. This implementation aimed to identify potential issues and disruptions that might arise during the actual instructional process. The details of both the pilot and main implementations are presented under separate subheadings below.

Pilot study

The pilot implementation was conducted to evaluate the validity and applicability of the lesson plans to be used in the main study. It was carried out at the end of the second semester of the 2020-2021 academic year with five students who had successfully completed the fifth grade and were about to begin the sixth grade. The implementation covered a single learning objective and was completed within two class hours. There were no time constraints during the sessions with the students.

Observations made at the end of the pilot implementation revealed insights regarding certain material requirements and time management. It was determined that students' motor skills were insufficient for cutting and pasting activities due to their age level, thus requiring more time. In addition, considering material shortages, it was concluded that in the main implementation, students should be provided with scissors in pairs, the number of glue sticks should be increased, and more mobile devices should be made available.

Main implementation

Prior to the main implementation, the physical and technological infrastructure of several middle schools located in a provincial city center in the western region of Turkey was examined. A school with suitable conditions for mobile device use was selected. Preliminary meetings were held with the school administration and science teachers to inform them about the aim of the research, the process, and the required equipment. After obtaining the necessary permissions, the implementation process began.

Before the implementation, the science teacher was introduced to the instructional content, the tools and materials to be used, and the assessment instruments. Although the instructional process was conducted by the researcher, the teacher was also involved in the process as an observer. Within this scope, the teacher was introduced to the AR application and was given the opportunity to experience it firsthand. The teacher had 17 years of experience in the field of science education, had participated in various projects, and was interested in contemporary instructional approaches. Therefore, they made significant contributions to both the instructional process and the research.

An AR-based instructional process was prepared for the students in the study group. The MAR application SPACE 4D+ was downloaded via Google Play, and the marker cards required for the application were obtained online. Since these cards could only be used with three mobile devices, students' access to mobile devices was determined in advance, and the necessary applications were installed on their devices. It was communicated to the school administration that mobile device use would be limited to the science course only, and the necessary permissions were obtained.

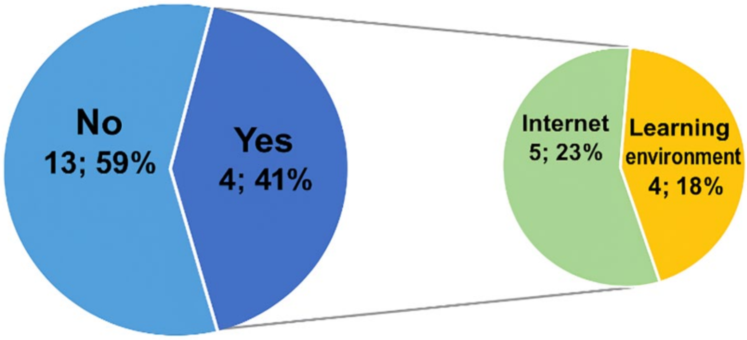

Figure 1. Students' pre-implementation knowledge about the MAR application (Generated by authors based on the data collected in this study)

The implementation was planned in accordance with the 5E instructional model. In the engage phase, a story related to the students' local environment was presented via a smartboard to capture attention, and students' prior knowledge was elicited through guiding questions (e.g., Have you ever observed the sky where you live? What did you see? Do you know the celestial bodies? Have you looked at the sky at different times of the day?). Following this, the AR application Galactic Explorer was used to deepen students' preexisting knowledge about the solar system.

In the explore phase, students were divided into groups of four, and each group was provided with a tablet or smartphone. Students were assigned the role of "explorers" and followed the steps outlined on the worksheet to complete discovery tasks. While no time issues arose during the pilot study, in the main implementation, students had difficulty completing all tasks within the allocated time and had to use recess periods to finish some of them. Students said that they missed hands-on activities such as cutting and pasting and enjoyed engaging in these types of tasks.

During the explain phase, students were asked various questions about the planets in the solar system (e.g., Which planet is closest to and farthest from the Sun? Which planet has the greatest and smallest mass in the solar system? Which planets have moons and which do not?). These questions enabled students to articulate scientific concepts.

In the elaborate phase, discussions were held on how information about celestial bodies could change over time through the use of AR. In particular, the meteor object captured students' interest, and they asked related questions with enthusiasm.

In the evaluate phase, students expressed what they had learned by organizing information in a chart. Each group wrote down the characteristics of celestial bodies on the AR cards they had created. After the instructional process was completed, the post-implementation student opinion form was administered. The overall research process progressed through five stages:

(1) preparation (lesson plan design and pilot study),

(2) implementation (main study with 22 students),

(3) data collection (pre- and post-forms),

(4) data analysis (inductive content analysis, κ, and thematic saturation), and

(5) reporting of findings.

These stages are detailed in the relevant subsections above.

FINDINGS

Findings Regarding the Pre-Implementation Student Opinion Form

The findings obtained from the analysis of the first question in the student opinion form ("Do you have any knowledge about MAR? If so, where did you acquire this knowledge?") are presented in **Figure 1**.

According to **Figure 1**, 59% (f = 13) of the students reported having no prior knowledge of AR applications, whereas 41% (f = 9) indicated that they were familiar with such tools. Among those with prior knowledge, the

Table 1. Students' expectations from AR applications

Theme	Subtheme	f	Example response
-	No response/ no specific expectation	5 (S4, S15, S16, S20, S22)	
Teaching-learning process	Learning about planets in detail	7 (S2, S6, S7, S8, S11, S13, S21)	(S11): "I expect to see the planets more clearly and in detail." (S13): "I guess we'll see moving images of the planets through MAR."
	Expectations for e-books (Z-books)	1 (S17)	(S17): "Books will be brought to schools, and when we press the book button, they will talk."
	An enjoyable and instructive experience	9 (S5, S7, S9, S11, S12, S14, S18, S19)	(S9): "I think it will be fun."
	Increased attention/interest in the course	2 (S1, S10)	(S10) : "I think this method will attract our attention because it's different, and it will help us focus more and increase our interest in the lesson."
	Faster access to information	1 (S3)	(S3): "We learn faster with mobile devices."

Internet (f = 5) and alternative instructional materials introduced by teachers (f = 4) were identified as the main sources of exposure. These findings suggest that while a notable proportion of students were already aware of AR technologies, their understanding was often superficial and based on informal experiences rather than systematic instruction. The high percentage of students with no prior knowledge highlights a gap in technological literacy, which in turn shaped the diversity of expectations expressed before the implementation. Moreover, the fact that some students encountered AR through teacher-led practices indicates that classroom innovations, even when sporadic, can influence students' awareness of emerging technologies.

In the second question of the student opinion form, students were asked about their expectations regarding the instruction to be delivered through MAR applications. The responses were categorized under themes and subthemes, as presented in **Table 1**.

As shown in **Table 1**, five students did not report any expectations, which may reflect their limited technological literacy or lack of familiarity with MAR applications. The majority of responses, however, clustered under the teaching-learning process theme, suggesting that students anticipated MAR would address the challenge of learning abstract astronomical concepts. Statements such as "I expect to see the planets more clearly and in detail" (S11) illustrate expectations for enhanced visualization, indicating that students associated MAR with the ability to make invisible or complex phenomena more concrete. In addition, expectations for digital resources, such as interactive e-books, point to an orientation toward more diversified and technology-rich learning environments.

The enjoyable and instructive experience subtheme, which included the highest number of responses, reflects an emphasis on the affective dimension of learning. Comments like "I think it will be fun" (S9) reveal that students valued enjoyment as a motivating factor alongside academic learning. Similarly, the increased attention/interest subtheme underscores the expectation that MAR would create more engaging lessons by attracting and sustaining focus (e.g., S10). Finally, the faster access to information subtheme highlights efficiency-related expectations, as students believed that MAR could reduce the time required to learn new content. Taken together, these findings indicate that students entered the implementation with both cognitive expectations (better visualization, faster learning) and affective expectations (enjoyment, increased attention), showing a multidimensional view of how MAR could shape their learning experience.

In the third question of the student opinion form, students were asked whether the instruction supported by the MAR application would contribute to the lesson in any way. The distribution of responses obtained is presented in **Figure 2**.

Upon examining **Figure 2**, it is observed that 91% (f = 20) of the students believed that instruction supported by MAR applications would contribute to their learning, while only 9% (f = 2) expressed the opposite view. This high level of perceived benefit indicates a strong initial belief in the instructional value of MAR. Such overwhelmingly positive expectations suggest that students anticipated not only content-related gains but

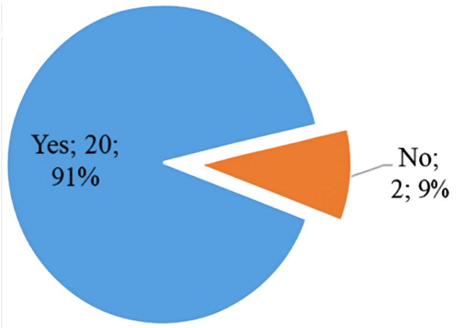

Figure 2. Students' opinions on whether AR applications would contribute to the course (Generated by authors based on the data collected in this study)

Table 2. Students' views on the contribution of MAR applications to the science course

Theme	Subtheme	f	Example response
No opinion	-	6 (S4, S5, S12, S14, S15, S19)	
Learning outcome	Better understanding of planets	5 (S1, S6, S13, S17, S21)	S13: "We are getting to know the planets better."
	Acquiring new knowledge/better learning	9 (S3, S7, S8, S9, S10, S11, S16, S18, S22)	S18: "It will contribute to the lessons; we will understand the topics better and improve our thinking skills." S22: "I think it will be more effective in my lessons."
Learning process	Visualization	2 (S2, S17)	S2: "I think we can use it to visualize it better in our minds." S17: "We can see the sun, earth, and moon in motion."
	A new experience	1 (S20)	S20: "It will be a brand-new experience."

also improvements in the overall learning process. In contrast, the few students who did not foresee any contribution may reflect a degree of skepticism toward new technologies or a lack of confidence in their own ability to adapt to such tools. These contrasting views highlight the diversity of students' readiness for technology-enhanced instruction, pointing to the importance of addressing both enthusiastic and hesitant learners in the classroom context.

The fourth question in the student opinion form asked, "What kind of contribution do you think instruction supported by MAR applications would make to the science course?" The responses were thematically categorized as shown in **Table 2**.

As shown in **Table 2**, six students did not provide any opinion on the potential contribution of MAR, which may reflect either limited prior exposure to such technologies or difficulty in articulating anticipated benefits. The remaining students' responses clustered under two broad themes: learning outcomes and learning processes.

Within the learning outcome theme, many students emphasized that MAR would lead to a better understanding of planetary concepts and the acquisition of new knowledge. For instance, statements such as "We are getting to know the planets better" (S13) and "We will understand the topics better and improve our thinking skills" (S18) indicate that students associated MAR with deeper and more effective conceptual learning. Such comments also suggest that students expected the technology to enhance not only factual recall but also higher-order thinking.

In terms of learning processes, students anticipated that MAR would improve the visualization of abstract concepts and provide novel learning experiences. For example, S2's remark, "I think we can use it to visualize it better in our minds," highlights the cognitive support expected from visual engagement, while S20's statement, "It will be a brand-new experience," reflects curiosity and openness to innovation. Together, these findings show that students perceived MAR as contributing to both the cognitive dimension of learning (understanding, knowledge acquisition) and the experiential dimension (visual support, novelty), reinforcing the dual role of MAR as both an instructional and motivational tool.

Table 3. Students' opinions about the instruction conducted with the MAR application

Theme	Subtheme	f	Example response
No opinion given	No opinion given	3(S5, S6, S7)	
Learning outcome	Cognitive knowledge	7 (S12, S13, S14, S15, S18, S21, S22)	S12: "It was amazing, I felt like I was seeing all the planets as if they were real." S14: "I was very impressed because it showed 3D visuals so well."
	Contribution of instructional process	6 (S2, S4, S10, S17, S19, S21)	S2: "I think it was nice and beneficial for learning." S17: "I believe education will further improve with MAR."
	Contribution of mobile applications	2 (S3, S11)	S11: "I've seen it before. It's a nice and useful application for education."
Learning process	Enjoyable environment	7 (S1, S7, S9, S10, S16, S18, S20)	S18: "In short, the instruction was very enjoyable. We understood the planets better." S16: "It was nice, we even launched a rocket into space."
	Broad impact	1 (S18)	S18: "... such applications should be used in every subject."
	Fast learning	1 (S9)	S9: "I think it was a very fun and nice application. I believe I learned the topic faster."

Findings Regarding the Post-Implementation Student Opinion Form

Following the instructional implementation, students' opinions regarding the MAR application were collected using the post-implementation student opinion form. In this context, the first question asked students about their thoughts on the instruction conducted with the MAR application. The responses were thematically categorized as shown in **Table 3**.

As shown in **Table 3**, three students did not express any opinions, while the remaining responses were grouped under the themes of learning outcomes and learning processes. Within the learning outcomes theme, students highlighted the role of MAR in enhancing cognitive knowledge and contributing to the instructional process. For example, comments such as "I felt like I was seeing all the planets as if they were real" (S12) and "I was very impressed because it showed 3D visuals so well" (S14) illustrate how the application transformed abstract planetary concepts into tangible experiences, strengthening spatial awareness. Similarly, statements like "I think it was nice and beneficial for learning" (S2) and "I believe education will further improve with MAR" (S17) reflect students' perception that MAR added pedagogical value by making lessons more effective and forward-looking.

The learning process theme captured the affective and experiential dimensions of students' reflections. The enjoyable environment subtheme, expressed by many students (e.g., S18: "The instruction was very enjoyable. We understood the planets better"), shows how enjoyment and motivation were intertwined with learning outcomes. Isolated but noteworthy responses also pointed to MAR's broad impact (S18: "Such applications should be used in every subject") and its role in fast learning (S9: "I believe I learned the topic faster"). Taken together, these findings indicate that students experienced MAR-supported instruction not only as a source of conceptual learning but also as an engaging and motivating process, suggesting a dual impact on both cognitive and affective domains.

The second question in the student opinion form asked whether the MAR application used during instruction met the students' expectations. The distribution of responses to this question is presented in **Figure 3**.

According to **Figure 3**, the MAR application met the expectations of 19 students, while only 3 students (S4, S5, S6) stated that it did not. The overwhelmingly positive responses suggest that the majority of students found the instructional experience aligned with or even beyond what they had anticipated, which reinforces the earlier pre-implementation findings where students expected MAR to enhance visualization, enjoyment, and engagement. The few students who reported unmet expectations may reflect a mismatch between their personal anticipations and the actual implementation, or difficulties related to confidence in using mobile technologies. These divergent perspectives highlight that while MAR can broadly meet learners' needs, individual differences in readiness and self-efficacy remain important factors influencing student satisfaction.

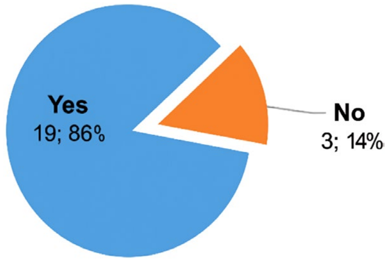

Figure 3. The extent to which the MAR application met students' expectations (Generated by authors based on the data collected in this study)

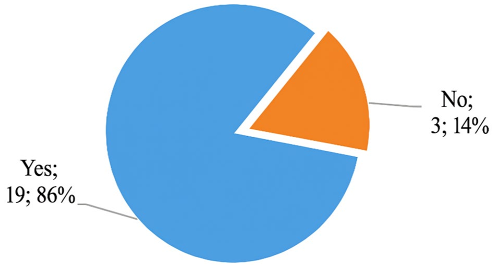

Figure 4. Students' views on the appropriateness of teaching the solar system and celestial bodies using MAR applications (Generated by authors based on the data collected in this study)

Table 4. Students' reasons for finding MAR suitable for learning the solar system and celestial bodies

Theme	Subtheme	f	Example response
Visual and realistic	Realistic experience	3 (S7, S12, S20)	S7: "People feel like they are actually in space."
	Visual support	2 (S11, S18)	S18: "… it's better to visualize it in our minds." S11: "Seeing it visually helps us remember."
Ease of learning	Fast learning	1 (S3)	S3: "The Solar System appeared right in front of me without even researching it."
	Memorability	1 (S11)	S11: "Seeing it visually helps us remember."
	Easy and instructive learning	2 (S16, S22)	S22: "Students both have fun and learn." S16: "We understand more easily."
Motivation	Learning through fun	4 (S9, S16, S21, S22)	S9: "We had fun and learned at the same time."
	Sparking curiosity	1 (S10)	S10: "People will use this app out of curiosity."

The third question in the student opinion form asked whether teaching the topic of the solar system using the MAR application was appropriate. The distribution of responses to this question is presented in **Figure 4**.

As shown in **Figure 4**, 19 students considered the use of MAR appropriate for teaching the solar system and celestial bodies, while 3 students (S4, S5, & S6) disagreed. Notably, these three students had also expressed that the application did not meet their expectations earlier, suggesting a consistent pattern of skepticism or difficulty in adapting to the technology.

Students who found the use of MAR appropriate for learning the topic of the solar system and celestial bodies were asked to explain their reasoning in the fourth question of the student opinion form. The responses were categorized thematically as presented in **Table 4**.

The justifications provided by students reveal three dominant themes: visual and realistic learning, ease of learning, and motivation (**Table 4**). The most frequent theme, visual and realistic learning, illustrates how students valued the sense of immersion and clarity offered by MAR. Statements such as "People feel like they are actually in space" (S7) and "Seeing it visually helps us remember" (S11) reflect how MAR supports visualization and strengthens memory, indicating a clear link to cognitive processes.

The ease of learning theme included references to faster comprehension, memorability, and more straightforward explanations. Comments like "The solar system appeared right in front of me without even researching it" (S3) and "We understand more easily" (S16) demonstrate that students perceived MAR as a tool that simplifies complex information and accelerates learning. Finally, the motivation theme emphasized the affective benefits of MAR. Students described the instruction as fun (S9: "We had fun and learned at the

Table 5. What students learned through MAR-based instruction on the solar system and celestial bodies

Theme	Subtheme	f	Example response
Planets	Various planets	6 (S9, S10, S12, S18, S19, S22)	S9: "I learned about the rotation, colors, and moons of the planets." S22: "I learned about the planets in more detail."
	Moons of planets	6 (S9, S11, S12, S15, S18, S21)	S11: "I learned how many moons each planet has."
Meteor	Characteristics of meteors	4 (S14, S15, S17, S20)	S14: "I saw the meteor I had only seen on TV before, now in 3D from space."
Asteroid	Characteristics of asteroids	3 (S7, S10, S13)	S7: "I didn't know there was an asteroid belt before. I learned that."
Sun	Characteristics of the sun	2 (S3, S8)	S3: "Thanks to the application, I orbited around the Sun."
Spacecraft	Artificial satellites	1 (S16)	S16
	Rockets	1 (S1)	S1: "We launched a rocket into space. I learned about rockets."
Did not learn	-	2 (S4, S6)	S4 & S6

same time") and curiosity-provoking (S10: "People will use this app out of curiosity"), suggesting that MAR not only engaged them emotionally but also fostered voluntary participation. Taken together, these findings show that students viewed MAR as both a cognitive aid (improving clarity and learning efficiency) and an affective stimulus (enhancing motivation and curiosity), which explains why the majority judged it highly appropriate for science instruction.

The fifth question asked students what they learned during the instruction of the solar system and celestial bodies supported by the MAR application. The responses were thematically categorized as shown in **Table 5**.

As shown in **Table 5**, students reported a wide range of learning outcomes, categorized under six themes. The most frequently mentioned category was planets, where students described learning new details about planetary features, such as rotation, colors, and moons (e.g., S9: "I learned about the rotation, colors, and moons of the planets"). These responses demonstrate how MAR facilitated conceptual depth, moving beyond superficial recognition toward more detailed understanding. Similarly, the moons of planets subtheme indicates that students gained concrete, previously unknown knowledge, exemplified by S11's remark, "I learned how many moons each planet has."

Other celestial bodies were also highlighted. The meteor and asteroid themes show that students were able to recognize and describe features of objects that are often overlooked in traditional instruction. S14's reflection, "I saw the meteor I had only seen on TV before, now in 3D from space," illustrates how MAR enhanced spatial perception and transformed abstract knowledge into lived experience. Likewise, S7's statement about discovering the asteroid belt points to the novelty of learning outcomes supported by visualization.

The sun theme emphasized how MAR provided an interactive, immersive experience, as expressed by S3: "Thanks to the application, I orbited around the sun." This illustrates how learning extended beyond observation to active engagement. The spacecraft theme further reveals how students connected natural celestial bodies with human-made technology, showing awareness of the interplay between science and technology (e.g., S1: "We launched a rocket into space").

Finally, two students reported that they did not learn anything new, which may reflect differences in prior knowledge, attention levels, or comfort with technology. Including such divergent responses strengthens the credibility of the analysis by acknowledging variability in learning outcomes. Overall, these findings suggest that MAR-supported instruction expanded students' conceptual repertoire across multiple domains, while also offering interactive and memorable experiences that traditional instruction may not easily provide.

The sixth question asked students whether they encountered any problems during the instruction supported by the MAR application. Additionally, if a problem was encountered, a follow-up question was posed to understand the nature of the issue in more detail. The responses were distributed as shown in **Figure 5**.

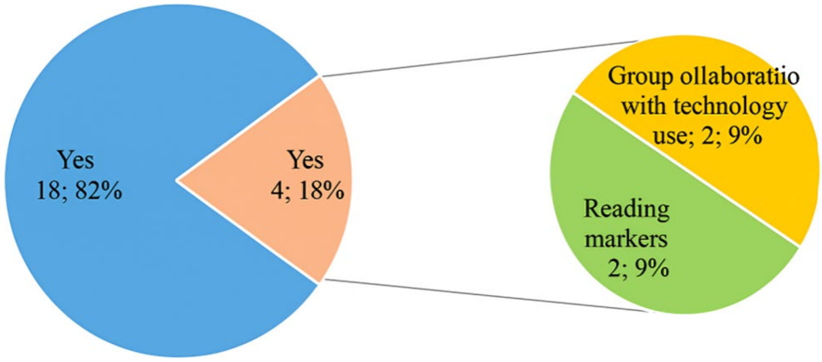

Figure 5. Occurrence of problems during instruction with MAR applications and the reported causes (Generated by authors based on the data collected in this study)

According to **Figure 5**, most students (f = 18) reported no difficulties, suggesting that the MAR application functioned smoothly and that the technological setup was largely effective. However, four students described specific challenges, pointing to two distinct categories of problems. First, technical difficulties emerged when the application had trouble scanning marker cards (S7 & S15), underscoring the sensitivity of MAR tools to hardware quality and environmental conditions such as lighting. These responses highlight that even small technical issues can disrupt the continuity of instruction. Second, difficulties related to group-based use of technology were mentioned by S4 and S6, who noted that managing devices in collaborative settings created challenges. This indicates that while MAR can enrich group learning experiences, careful planning of device distribution and task coordination is critical.

Together, these findings show that although MAR was generally perceived as user-friendly and reliable, minor but important barriers persisted. Addressing such challenges requires attention both to the technical infrastructure and to the pedagogical organization of classroom activities, ensuring that the potential of MAR is not diminished by avoidable obstacles.

CONCLUSION

This study investigated the effects of MAR-supported science instruction on middle school students' conceptual understanding and motivation in learning astronomy. The results demonstrate that MAR can effectively make abstract astronomical phenomena more concrete and engaging, leading to both cognitive and affective gains. These outcomes reaffirm prior findings that highlight AR's potential for enhancing visualization, comprehension, and curiosity in science learning (Bacca et al., 2014; Chang et al., 2014; Ibáñez & Delgado-Kloos, 2018), while extending the evidence to younger learners with limited prior exposure to AR technologies.

Beyond confirming earlier results, this research contributes context-specific insights from a Turkish public school environment, illustrating that MAR integration can succeed even under moderate infrastructural limitations. In doing so, the study bridges global AR literature with local educational realities and aligns with recent trends emphasizing contextual adaptation of educational technologies (Simon et al., 2025; Zhang & Yao, 2025).

From a practical standpoint, the findings indicate that MAR can serve as a pedagogically powerful tool for fostering inquiry-based, student-centered science instruction in alignment with the 2024 Turkish science curriculum. However, the study also revealed constraints related to device functionality, marker recognition, and group management, suggesting that effective implementation depends not only on the availability of technology but also on teacher preparedness and classroom design. Therefore, it is recommended that teachers receive targeted professional development on AR pedagogy, including classroom management in technology-rich lessons, and that schools ensure stable technical infrastructure.

From a research perspective, future studies could examine longitudinal effects of MAR on conceptual retention, investigate cross-grade or cross-discipline implementations, and employ mixed-method designs to quantify observed affective outcomes. Moreover, comparative studies between high- and low-resource school settings could clarify how contextual variables mediate the success of MAR interventions.

In summary, this study underscores that MAR-supported learning environments can simultaneously promote engagement and conceptual understanding when grounded in sound pedagogical design. By highlighting both potential and limitation, this research offers a balanced view of how emerging technologies like MAR can contribute to equitable, inquiry-driven, and contextually relevant science education.

DISCUSSION

The findings of this study show that MAR-supported instruction had a dual impact on students' learning: it enhanced conceptual understanding of astronomical phenomena and fostered motivation and enjoyment during the learning process. Students emphasized that MAR allowed them to visualize planets, meteors, and asteroids in greater detail, which aligns with prior studies highlighting the role of AR in concretizing abstract scientific concepts (Chang et al., 2014; Ibáñez & Delgado-Kloos, 2018; Ibáñez et al., 2014). Similar results were reported by Şahin (2017), who found that MAR-supported instruction contributed to achievement in astronomy-related topics. More recent evidence supports these findings: Sattar et al. (2025) confirmed that AR-based science learning environments significantly enhance both conceptual comprehension and student engagement across multiple grade levels. Likewise, the meta-review by Yang et al. (2025) underscored the growing effectiveness of mobile AR applications in scaffolding learners' spatial reasoning and visualization skills. Our findings extend this emerging body of work by demonstrating that conceptual depth and engagement can also be achieved with younger learners who have limited prior exposure to AR technologies, underscoring the accessibility of MAR across grade levels.

Beyond cognitive gains, the affective and motivational dimensions observed in this study echo earlier findings. Students consistently described the experience as enjoyable and curiosity-provoking. Xiao et al. (2018) similarly reported high school students' willingness to use MAR in astronomy, while Chen et al. (2022) highlighted its role in promoting creativity, contextual learning, and engagement. Bacca et al. (2014) and Abdüsselam and Karal (2012) also found that AR increased students' participation and curiosity in science classes. These trends are corroborated by Sattar et al. (2025), who noted that affective engagement is a major determinant of learning persistence in AR-supported environments. Collectively, these parallels suggest that MAR creates a learning environment that integrates enjoyment with meaningful knowledge acquisition. Importantly, the present study extends prior work by illustrating how MAR can sustain motivation in middle school settings, where students may otherwise struggle with abstract astronomical content.

Despite these benefits, some students reported challenges. Four students mentioned either marker recognition issues or difficulties in group-based use of technology. These findings confirm the technical sensitivities identified by İbili and Şahin (2013), who emphasized the role of environmental factors such as lighting in marker detection. Furthermore, group management challenges point to the importance of designing pedagogical strategies alongside technological integration. Unlike many studies that predominantly report positive outcomes (Wu et al., 2013), our results reveal a more nuanced picture by highlighting how infrastructural and organizational constraints can hinder MAR's effectiveness. Zhang and Yao (2025) similarly observed that AR adoption in classroom contexts is limited by factors such as device availability, connectivity, and teacher preparedness. In addition, previous research has shown that while AR increases achievement and motivation, its implementation can be undermined by technical glitches and insufficient instructor support (Akçayır & Akçayır, 2017; Bacca et al., 2014). A distinctive contribution of this study lies in situating the findings within the Turkish science education context. The 2018 science curriculum emphasized constructivist and inquiry-based approaches, particularly the 5E instructional cycle, while the 2024 revision strengthened the integration of STEM, digital literacy, and innovative learning environments (Milli Eğitim Bakanlığı [MEB], 2018, 2024). The alignment between students' positive responses and these curricular priorities highlights MAR's potential as a tool for national educational transformation. At the same time, the technical and pedagogical challenges observed in this study reflect the infrastructural limitations of many Turkish public schools. This contrast underscores the dual reality of MAR in practice: while it aligns with forward-looking curricular visions, its success depends on addressing the contextual constraints of implementation. Similar observations were made by Simon et al. (2025), who emphasized that successful AR integration depends not only on technology but also on the degree to which it is embedded in authentic educational contexts and supported by institutional readiness.

Taken together, these results contribute to the broader international literature by offering evidence that MAR not only supports cognitive and affective learning outcomes but also exposes the challenges of real-world classroom integration. By highlighting both opportunities and limitations, this study provides a more balanced perspective on the role of MAR in science education. To address the issues identified, this study recommends teacher professional development focused on AR pedagogy, improved technical infrastructure, smaller collaborative groupings, and pre-implementation orientation sessions. These actionable insights resonate with global findings calling for a balance between technological affordance and instructional manageability (Simon et al., 2025; Zhang & Yao, 2025). The novelty of this research thus lies in demonstrating how a globally emerging technology can be adapted to national curricula while remaining sensitive to local classroom realities.

While these findings demonstrate the multifaceted contributions of MAR to the learning process, the study's distinctive scientific contribution becomes particularly evident when examined through its contextual and practice-based dimensions.

The scientific contribution of this study lies in its context-specific and practice-based insights into how MAR-supported instruction functions within a typical public school environment characterized by limited technological infrastructure. The findings demonstrate how well-known challenges reported in the literature–such as marker recognition issues, insufficient device availability, and the complexities of group-based use–shape the implementation process, supporting earlier claims that the effectiveness of AR applications is strongly influenced by contextual and infrastructural factors (Garzón & Acevedo, 2019; Zhang & Yao, 2025). Furthermore, the preparation of the teacher prior to implementation, the structured use of the 5E instructional model, and the alignment of activities with the national science curriculum illustrate how MAR integration is shaped by pedagogical design and curriculum requirements. The emphasis on student experiences provides an additional contribution by responding to recent calls for AR/MAR research that prioritizes learner perspectives and authentic classroom contexts (Simon et al., 2025). In this respect, the study not only highlights the cognitive and affective benefits of MAR but also offers a nuanced understanding of the practical dynamics encountered in real classroom settings, thereby addressing a notable gap in the AR/MAR literature.

Recommendations

Classroom practice

1. Group work with MAR should be limited to small groups (no more than three students) to reduce coordination difficulties and ensure active participation.
2. Schools should provide a sufficient number of mobile devices so that students can engage individually with the technology.
3. Activity density should be moderated by reducing the number of tasks and allocating more time for exploration, explanation, and evaluation phases.
4. Balanced natural lighting conditions should be ensured to prevent marker recognition problems.
5. A short orientation session before implementation can help students gain confidence and improve their self-efficacy in using MAR.
6. MAR content should be closely aligned with curriculum objectives and tailored to students' developmental levels to better support conceptual learning.

Future research

1. Studies with larger and more diverse samples are recommended to examine how different school infrastructures affect MAR integration.
2. Comparative research across countries could reveal how cultural and educational contexts influence students' perceptions of MAR.

3. Longitudinal or mixed-method studies are needed to explore not only immediate perceptions but also long-term effects on conceptual change, motivation, and digital literacy.
4. Future work might also focus on teacher professional development, investigating how teachers' technological pedagogical knowledge (TPACK) influences the effective use of MAR in science education.

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APPENDIX A: STUDENT OPINION FORMS

Student Opinion Form (Pre-Implementation)

Name-Surname: .... **Gender:** ....

1. Do you have any knowledge about mobile augmented reality?
   Yes ( ) No ( )
   If yes, briefly explain how you obtained this information.
   ....
2. What are your expectations from instruction supported by mobile augmented reality? Please explain briefly.
   ....
3. Do you think instruction supported by mobile augmented reality will contribute to the science course?
   Yes ( ) No ( )
4. If you think it will contribute to the science course, briefly explain how.
   ....

Student Opinion Form (Post-Implementation)

Name-Surname: .... **Gender:** ....

1. What are your thoughts on the instruction conducted with mobile augmented reality? Please explain briefly.
   ....
2. Did it meet your expectations? Please explain briefly.
   ....
3. In your opinion, is it appropriate to learn the topic of the Solar System and celestial bodies through mobile augmented reality?
   Yes ( ) No ( )
4. If you think it is appropriate, briefly explain why.
   ....
5. What did you learn about the Solar System and celestial bodies through mobile augmented reality?
   ....
6. Did you encounter any problems while using mobile augmented reality during the lesson?
   Yes ( ) No ( )
   If you did encounter a problem while using mobile augmented reality, briefly explain what it was.
   ....