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Evaluating the Feasibility and User-Friendliness of an Augmented Reality–Integrated Physics Textbook on Motion Dynamics

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Abstract *- Physics learning in the 21st century requires interactive, technology-enhanced instructional resources that support students' understanding of abstract concepts, particularly those related to the dynamics of motion. However, many augmented reality (AR)-based learning tools remain limited to standalone applications and are not adequately integrated into structured instructional materials, which may reduce their pedagogical value and classroom usability. Therefore, this study aimed to develop and evaluate an Augmented Reality Integration (ARI)-based physics textbook designed to improve the feasibility and user-friendliness of AR-supported learning materials in physics education. The study employed a development research approach based on the design thinking model, comprising five stages: empathize, define, ideate, prototype, and test. The ARI textbook was developed by integrating textbook content, student worksheets, and marker-based augmented reality features into a unified learning resource on motion dynamics. Data were collected through literature review, observations, interviews, expert validation, and usability testing involving teachers and students. Feasibility was assessed using Gregory's expert agreement analysis, while usability and user experience were evaluated using the System Usability Scale (SUS) and the User Experience Questionnaire (UEQ). The results showed that the developed textbook achieved a Gregory coefficient of 1.00 for both content and language, indicating a high level of feasibility for classroom use. The SUS results further indicated that the textbook was acceptable for learning, although differences were found between Grade X and Grade XII students in terms of ease of use and independence. In addition, the UEQ results demonstrated improvements across all users experience dimensions after iterative refinement, particularly in stimulation, attractiveness, and perspicuity. The novelty of this study lies in integrating augmented reality into a structured physics textbook, developed through a user-centered design thinking approach, rather than as a standalone application. In conclusion, the ARI-based textbook is feasible and user-friendly, and it contributes to physics education by providing an innovative, interactive, and pedagogically meaningful learning resource for visualizing abstract concepts.*

Keywords: *augmented reality; AR-integrated textbook; motion dynamics; physics education; user experience.*

I. INTRODUCTION

The global education system has entered the era of 21st-century learning, which emphasizes higher-order thinking and essential competencies, including creativity, critical thinking, communication, and collaboration (4Cs) (Cheng, 2017; Voogt & Roblin, 2012). This paradigm promotes student-centered learning environments that encourage active engagement, problem-solving, and meaningful knowledge construction (Bernard et al., 2017). In Indonesia, these principles are reflected in the Merdeka Curriculum, which emphasizes scientific inquiry, conceptual understanding, and process skills in physics education (BSKAP Kemdikbudristek, 2022a, 2022b). Accordingly, the integration of digital technology into learning environments is increasingly important to support these competencies.

The rapid development of digital technology has substantially transformed educational practices. In Indonesia, mobile device usage exceeds 60% of the population, indicating strong potential for integrating mobile-based learning (Sutarsih & Maharani, 2020). Recent studies have shown that digital and immersive learning technologies, including Augmented Reality (AR) and Virtual Reality (VR), can enhance flexibility, accessibility, engagement, and conceptual understanding in learning environments (Nurhidayah et al., 2025; Radianti et al., 2020; Volioti et al., 2022). Systematic reviews further suggest that immersive technologies provide meaningful and interactive learning experiences that foster deeper understanding of complex concepts (Garzón et al., 2019).

In science and physics education, the integration of information and communication technology plays a particularly important role because many scientific concepts are inherently abstract. Previous research indicates that AR is especially effective for visualizing abstract phenomena and supporting STEM learning (Ibáñez & Delgado-Kloos, 2018). In physics learning, visualization is essential for helping students understand dynamic and complex concepts such as motion and forces. Studies have shown that AR-based immersive learning environments can improve conceptual understanding, motivation, and self-efficacy (Makransky & Mayer, 2022). In addition, AR has been found to increase student satisfaction and engagement while supporting meaningful learning experiences (Sirakaya & Cakmak, 2018; Bower et al., 2014).

Recent studies further confirm that AR can significantly improve learning outcomes, motivation, engagement, and retention in STEM education (Wahyudi et al., 2024; Garzón et al., 2019). AR also supports the development of students' visual-spatial abilities and strengthens their understanding of scientific concepts through interactive learning environments (Bower et al., 2014). Moreover, recent narrative reviews indicate that the use of AR in education has increased substantially in recent years, particularly in STEM contexts, while also highlighting persistent challenges, such as the lack of standardized frameworks and implementation guidelines (Pallavicini & Anesa, 2026).

Despite these advantages, several limitations remain in implementing AR in education. Most existing studies focus on standalone AR applications or short-term experimental tools rather than integrating AR into structured instructional materials such as textbooks or teaching modules (Ibáñez & Delgado-Kloos, 2018; Radianti et al., 2020; Garzón et al., 2019). In addition, many AR-based learning tools are developed from a technology-driven perspective, with limited attention to usability, user experience, and learner needs. This limitation may reduce the effectiveness and sustainability of AR integration in actual classroom settings.

Another important gap is the limited application of user-centered design approaches, such as design thinking, in the development of AR-based learning materials. Design thinking emphasizes empathy, iterative prototyping, and continuous user feedback, making it highly relevant for developing effective and user-friendly educational products (Razzouk & Shute, 2012; Henriksen et al., 2017). Furthermore, usability and user experience are critical to the success of AR-based learning tools. Previous studies have shown that usability significantly influences students' satisfaction, engagement, and learning effectiveness in AR environments (Bower et al., 2014; Sirakaya & Cakmak, 2018). However, research integrating AR-based physics textbooks with a design thinking framework while simultaneously evaluating usability remains limited.

To address these gaps, this study proposes developing an Augmented Reality Integration (ARI) physics textbook using a design thinking approach. The ARI textbook incorporates Marker-Based Augmented Reality (MB-AR) into three key components: (1) an interactive AR-based textbook that allows students to engage with physics concepts more actively, (2) AR-supported student worksheets that enhance problem-solving and visualization, and (3) AR-based learning media designed to make abstract concepts in the dynamics of motion more accessible through visual representation. Unlike previous studies that mainly focused on creating standalone AR applications, this study emphasizes seamless integration of AR into structured instructional materials, with a strong focus on usability and enhancing user experience to support meaningful learning.

Therefore, this study aims to evaluate the feasibility and user-friendliness of the ARI textbook, which was developed using a design thinking approach. This research makes a significant contribution to physics education by introducing an innovative, user-centered AR-based learning resource. Additionally, it offers valuable insights into the process of developing effective, technology-enhanced instructional materials in science education.

II. METHODS

This study employed a development research approach using the design thinking model to develop an ARI-based physics textbook. According to the Institute of Design at Stanford, as presented in the Bootleg Design Thinking, the design thinking process consists of five stages: empathize, define, ideate, prototype, and test, as illustrated in Figure 1. These stages were implemented systematically to ensure that the developed product was user-centered, pedagogically appropriate, and feasible for classroom implementation.

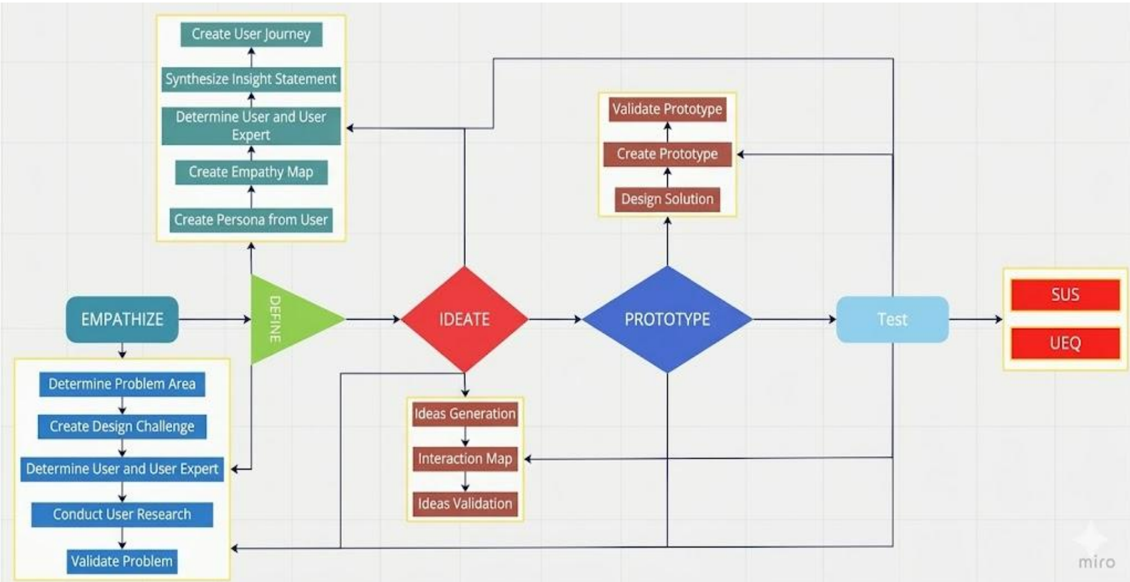


Figure 1. Research flowchart

1. Empathize

At this stage, data were collected through a literature review, classroom observations, and semi-structured interviews involving four physics teachers and 256 students from two senior high schools. The participants were selected using purposive sampling based on their involvement in teaching and learning physics, particularly in the topic of dynamics of motion.

The empathize stage focused on identifying students' learning difficulties, especially in understanding abstract physics concepts, as well as teachers' needs for more interactive and effective instructional materials. The outputs of this stage included empathy maps, user personas, and user journey maps that represented learning challenges from both the student and teacher perspectives.

2. Define

The collected data were organized, analyzed, and synthesized to identify the core problems in physics learning. This stage aimed to determine the gap between existing learning resources, such as conventional textbooks, and students' learning needs. The analysis resulted in clearly formulated problem statements and learning objectives that emphasize the need for interactive, visual, and engaging teaching materials aligned with the Merdeka Curriculum.

3. Ideate

In the ideation stage, brainstorming sessions were held to generate potential solutions to the identified problems. Several design alternatives were proposed, including the integration of 3D visualizations, animations, and marker-based AR into the textbook. This stage also involved reviewing available AR platforms and aligning them with pedagogical requirements. The output of this stage was a conceptual design of the ARI-based textbook, including the content structure, AR marker integration, and student worksheets.

4. Prototype

The conceptual design was then developed into a prototype of the ARI-based physics textbook. This process involved designing the textbook layout, embedding AR markers, and developing a mobile-based AR application capable of displaying 3D visualizations. The prototype was developed iteratively to improve usability, including refinements to the user interface, visualization quality, and integration of the textbook content with AR features.

5. Test

At the testing stage, the feasibility and user-friendliness of the developed ARI-based physics textbook were evaluated through expert validation and usability testing, with ethical research principles applied throughout. Expert validation was conducted by two validators: one physics education expert and one instructional media expert. The validation process employed the Gregory content validity model to assess experts' level of agreement on the relevance and appropriateness of each component of the developed product. The evaluation was based on several criteria, including content accuracy, conceptual clarity, media design quality, integration of AR features, and alignment with curriculum objectives. The Gregory formula was then used to calculate the content validity coefficient, and the results were interpreted according to established validity categories: very high, high, moderate, and low.

Furthermore, usability testing was conducted to evaluate the practicality and user experience of the ARI-based textbook. This stage involved 256 students and 5 physics teachers who had not participated in the initial needs analysis. The participants were selected using purposive sampling to ensure that they represented the actual users of the developed product. The evaluation instruments included the System Usability Scale (SUS) to measure overall usability and the User Experience Questionnaire (UEQ) to assess aspects of user experience, such as attractiveness, efficiency, and stimulation. The collected data were analyzed descriptively to determine the level of user-friendliness and user acceptance of the ARI-based textbook.

In addition, this study adhered to ethical research standards. All participants were informed about the purpose of the study and provided informed consent prior to participation. Participation was voluntary, and participants had the right to withdraw at any stage without any consequences. All collected data were kept confidential and used solely for research purposes. Through this testing stage, the development process not only ensured the technical feasibility of the ARI-based physics textbook but also addressed pedagogical relevance, usability, and user needs. Therefore, the developed textbook is expected to be feasible, user-friendly, and effective for use in physics instruction, particularly on the topic of motion dynamics.

III. RESULTS

The SWOT analysis presented in Figure 2 indicates that one of the main difficulties in learning physics is the subject's abstract nature, which often leads to misconceptions (Treagust, 2007; Çalik et al., 2005). Existing 3D media have not yet been able to comprehensively visualize these concepts (Akçayır & Akçayır, 2017). However, the development of AR/VR technologies and the increasing use of smartphones each year provide significant opportunities to introduce innovations, such as AR-based textbooks, that can help students better understand abstract concepts (Bacca et al., 2014; Ibáñez & Delgado-Kloos, 2018).

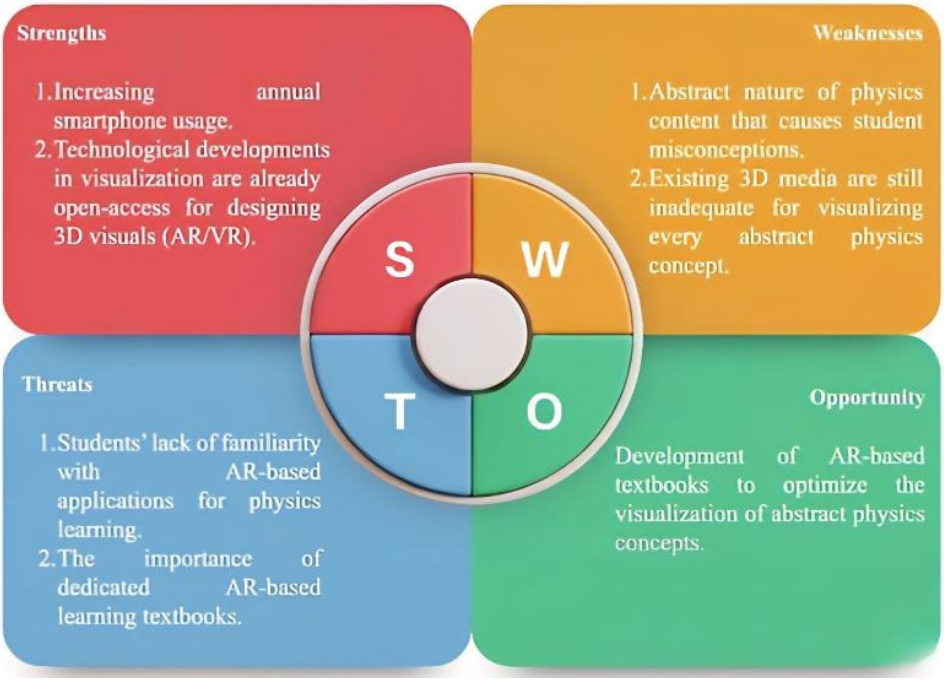


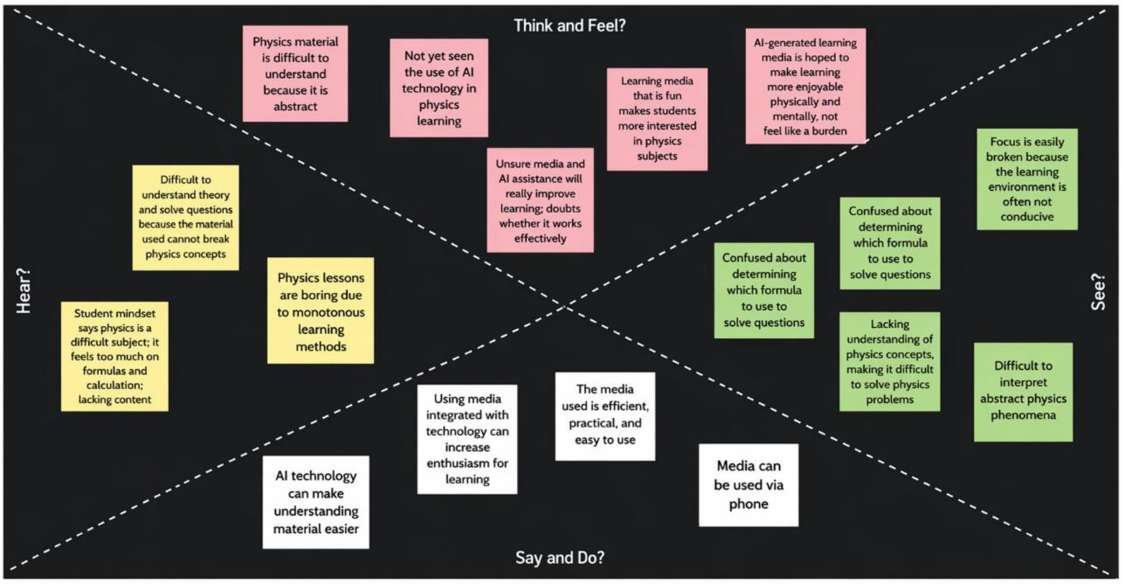
Figure 2. SWOT schema

On the other hand, the identified challenges include students' limited experience with AR-based applications and a lack of adequate AR-based textbooks (Cai et al., 2017). To address these issues, the researcher designed a research plan to both understand the identified problems and confirm the proposed solutions. This research plan covered six key points: design challenge, researcher profile, identification of users and stakeholders, informants, research plan, and interview guide (Dam & Teo, 2024).

Furthermore, the empathy map results shown in Figure 3 indicate that students often struggle to understand physics concepts due to their abstract nature and the limited availability of visual media. This condition makes students easily bored and prone to misconceptions (Treagust, 2007; Çalik et al., 2005). Teachers face similar difficulties, as they must repeatedly explain the material using conventional methods, making the learning process less efficient.

Students reported that the media used in learning were still limited to textbooks or two-dimensional (2D) presentations, whereas teachers recognized that technologies such as AR have the potential to support learning but are not yet adequately available (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018). Students also heard many complaints from classmates about the difficulty of understanding physics, while teachers experienced pressure from schools and parents to provide more innovative and interactive learning (Bacca et al., 2014).

Ultimately, students expressed the need for learning media that are interactive, engaging, and easy to use, even without internet access, while teachers required practical tools to support teaching efficiency. These findings reinforce the importance of developing an ARI-based textbook capable of accommodating the needs of both students and teachers (Cai et al., 2017; Dam & Teo, 2024).



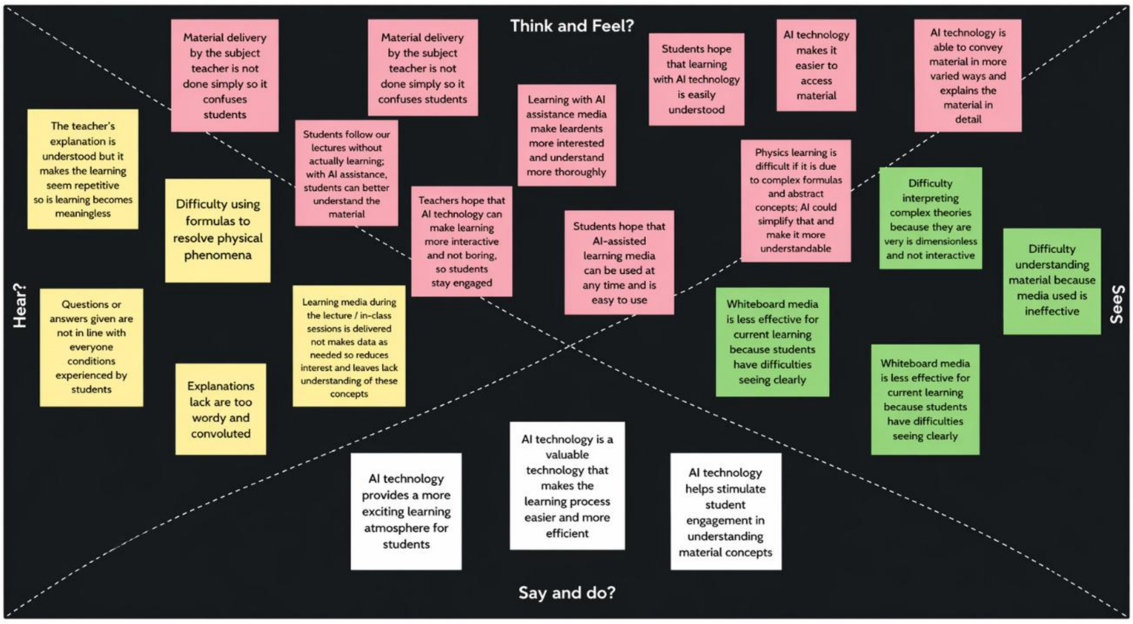


Figure 3. Empathy map in several schools

Based on the user journey data illustrating students' experiential flow during physics learning with existing media, Figure 4 shows that the yellow line represents students' learning experiences. Initially, these experiences were limited to the use of two-dimensional (2D) textbooks, which tend to be static and less interactive (Picciano, 2017). Over time, learning evolved to use limited three-dimensional (3D) media that provided more concrete representations. However, these media still had limitations regarding interactivity (Roussou, 2004). This condition led to students' expectations regarding the use of Augmented Reality (AR) technology, which can provide more immersive, interactive, and contextual visualizations (Azuma, 1997). These expectations were subsequently directed toward the development of an AR-based module to meet the needs of physics learning in a more engaging, interactive, and contemporary manner (Elmqaddem, 2019).

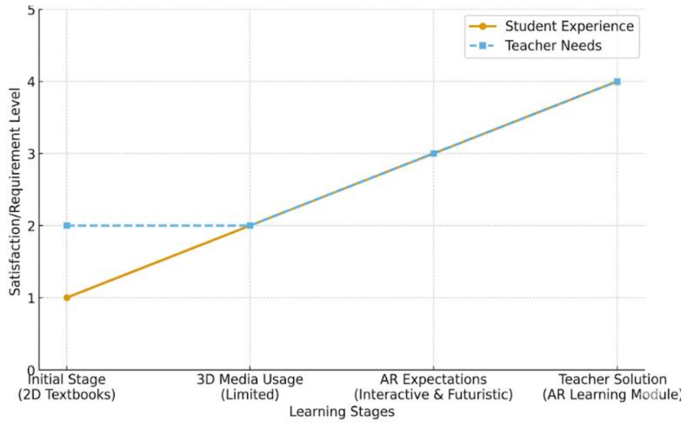


Figure 4. User journey in several schools

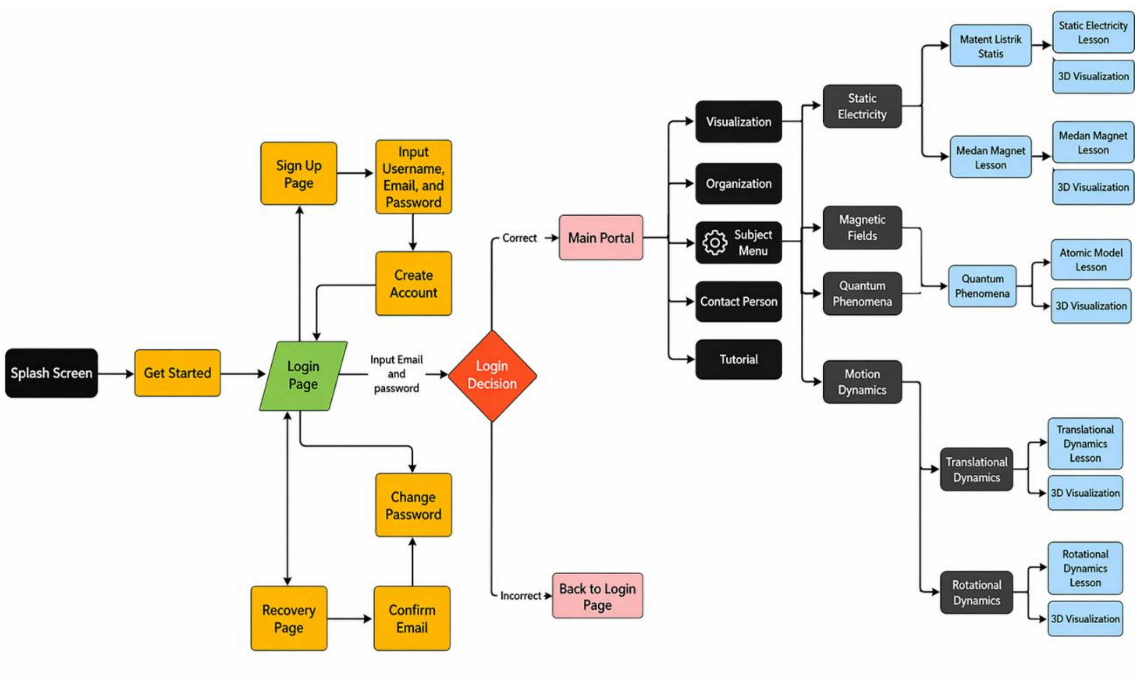


Figure 5. Interaction map of PyLo-AR

Based on the results of the empathy map and user journey, brainstorming activities generated feature ideas that were incorporated into the interaction map of the PyLo-AR application to support the AR-based textbook, as shown in Figure 5. Following the flow of this interaction map, the user interface designs for the PyLo-AR application and the AR-based textbook were developed using CorelDRAW, Figma, and Canva. The visual appearances of the PyLo-AR application and the AR-based textbook are presented in Figures 6 and 7.

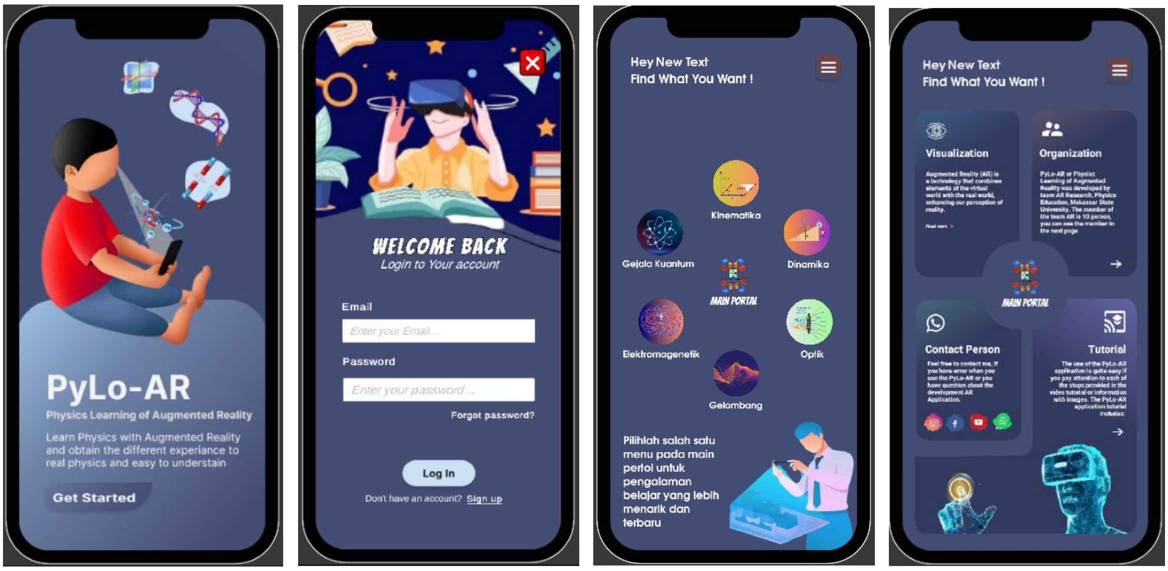
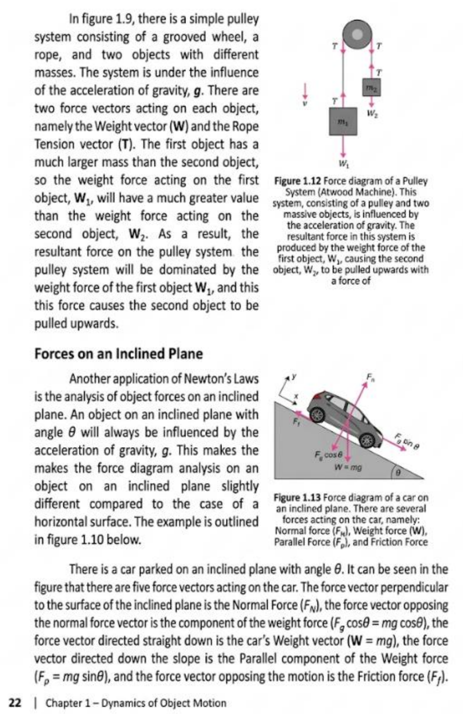


Figure 6. User journey in several schools

The PyLo-AR application and the AR-based textbook were successfully designed using a solution-oriented design approach to ensure usability and convenience for students. The core feature of the PyLo-AR application is a marker detection system that enables the display of 3D visualizations within the textbook, allowing students to observe physics concepts visually, particularly motion dynamics, which is the focus of this study. Each marker embedded in the textbook represents specific concepts related to motion dynamics.



In figure 1.9, there is a simple pulley system consisting of a grooved wheel, a rope, and two objects with different masses. The system is under the influence of the acceleration of gravity, *g*. There are two force vectors acting on each object, namely the Weight vector (**W**) and the Rope Tension vector (**T**). The first object has a much larger mass than the second object, so the weight force acting on the first object, W_1, will have a much greater value than the weight force acting on the second object, W_2. As a result, the resultant force on the pulley system the pulley system will be dominated by the weight force of the first object W_1, and this this force causes the second object to be pulled upwards.

Figure 1.12 Force diagram of a Pulley System (Atwood Machine). This system, consisting of a pulley and two massive objects, is influenced by the acceleration of gravity. The resultant force in this system is produced by the weight force of the first object, W_1, causing the second object, W_2, to be pulled upwards with a force of

Forces on an Inclined Plane

Another application of Newton's Laws is the analysis of object forces on an inclined plane. An object on an inclined plane with angle θ will always be influenced by the acceleration of gravity, *g*. This makes the makes the force diagram analysis on an object on an inclined plane slightly different compared to the case of a horizontal surface. The example is outlined in figure 1.10 below.

Figure 1.13 Force diagram of a car on an inclined plane. There are several forces acting on the car, namely: Normal force (F_N), Weight force (W), Parallel Force (F_p), and Friction Force

There is a car parked on an inclined plane with angle θ. It can be seen in the figure that there are five force vectors acting on the car. The force vector perpendicular to the surface of the inclined plane is the Normal Force (F_N), the force vector opposing the normal force vector is the component of the weight force ($F_g \cos\theta = mg \cos\theta$), the force vector directed straight down is the car's Weight vector (**W** = *mg*), the force vector directed down the slope is the Parallel component of the Weight force ($F_p = mg \sin\theta$), and the force vector opposing the motion is the Friction force (F_f).

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Figure 7. An AR–based textbook on motion dynamics

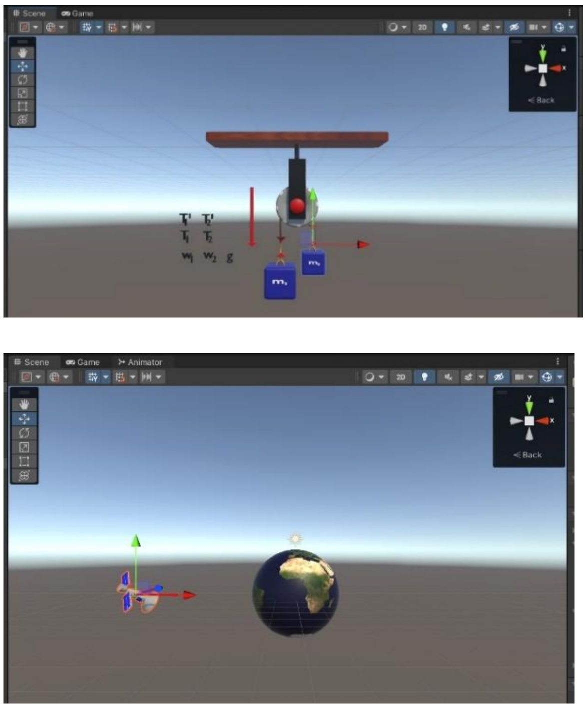

Figure 8. 3D visualization of the force diagram

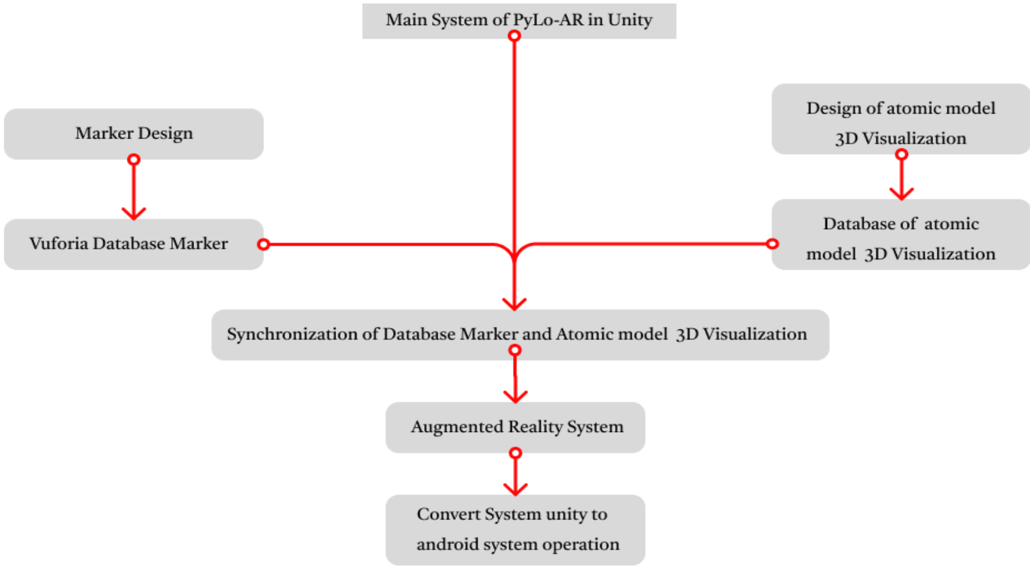

Figure 9. Augmented Reality system diagram of the AR-based textbook

Furthermore, the components of the PyLo-AR application were integrated with a complete set of 3D visualizations of motion-dynamics material, synchronized with the Augmented Reality system and the marker database on the Vuforia platform, as illustrated in the PyLo-AR application system diagram in Figure 9. In addition, the 3D visualizations included in the PyLo-AR application and the AR-based textbook cover Newton's laws, centrifugal force, free-body diagrams, equilibrium, torque, and moment of inertia. One example of the 3D visualization design is shown in Figure 8.

The next stage involved testing the AR-based textbook and the PyLo-AR application system. This testing included a feasibility evaluation of the AR-based textbook using Gregory's two-expert agreement analysis. The results show that the Gregory internal agreement coefficients for both content and language exceeded 0.80, indicating that the AR-based textbook's content and language are suitable for use in the learning process. Based on the feasibility test results, as agreed upon by the two experts, the AR-based textbook is appropriate for use in physics instruction.

In addition, the usability of the AR-based textbook was evaluated using the SUS, which assesses adjective ratings, grade scales, and acceptability ratings. The results of this usability testing are presented in Table 1 and in the SUS scale diagrams shown in Figures 10 and 11.

Table 1. SUS results

School	Grade	SUS score	SUS grade	School
SMAN 2 Makassar	X	53	D	X
	XII	70	C	XII
SMAN 11 Makassar	X	53	D	X
	XII	70	C	XII

The results of the SUS testing on the AR-based textbook at SMAN 2 Makassar and SMAN 11 Makassar indicate relatively similar outcomes between Grade X and Grade XII students. At SMAN 2 Makassar, Grade X students obtained a SUS score of 53, which reflects a marginal level of acceptability, with the application quality classified as grade "D" and an adjective rating of "OK." This result indicates that the application is usable but still requires improvements and user guidance. Meanwhile, Grade XII students achieved a SUS score of 70, placing the application at grade "C" with a marginal-high level of acceptability, suggesting that the application is relatively easy to use and acceptable despite several technical issues (Sukma et al., 2023).

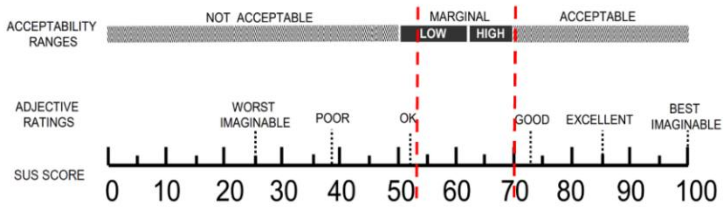

Figure 10. SUS evaluation scale at SMAN 2 Makassar

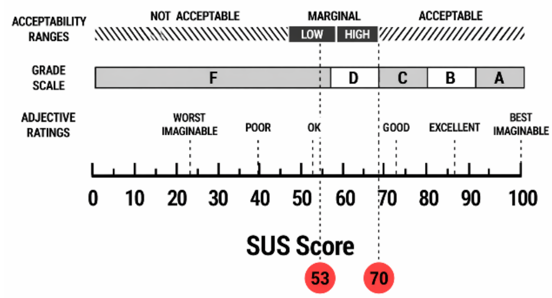

Figure 11. SUS evaluation scale at SMAN 11 Makassar

Based on the test results from both schools, the AR-based textbook is considered feasible for use in learning. Grade X students required more time and guidance to use the application, whereas Grade XII students demonstrated greater independence and perceived the application as aligned with the learning objectives. Overall, the SUS results indicate that the AR-based textbook has good potential for wider implementation, although further improvements are still needed to enhance the user experience (Hasan et al., 2025; Gräser, et al., 2024).

The subsequent evaluation employed the UEQ, which was analyzed using the UEQ Data Analysis Tool. The UEQ analysis produced several parameters across the six UEQ indicators, namely attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty, to assess the user-friendliness of the AR-based textbook. The UEQ measurements were conducted in two stages: during the initial use of the AR-based learning module and after students had used the AR-based textbook for one week. The resulting parameters from the UEQ analysis are presented in Table 2.

Table 2. Descriptive statistics results of each UEQ indicator

Indicators of UEQ	UEQ scales (mean and variance)			
	First testing phase		Second testing phase	
	Mean	Variance	Mean	Variance
Attractiveness	1.256	1.178	1.797	0.659
Perspicuity	1.008	1.674	1.700	1.084
Efficiency	1.100	1.313	1.577	0.870
Dependability	1.308	1.149	1.605	0.728
Stimulation	1.475	1.407	1.941	0.722
Novelty	1.158	1.006	1.231	0.432

Table 2 presents the descriptive analysis results for each UEQ indicator based on 55 samples. The indicator with the highest mean score in the first testing phase was stimulation (1.475), while the lowest mean score was perspicuity (1.008). The graphical results show improvements across all UEQ indicators after using the AR-based textbook, indicating that students required approximately 1 week to become accustomed to using the AR-based learning module independently. Therefore, the AR-based textbook has the potential to serve as interactive support for students' self-directed learning.

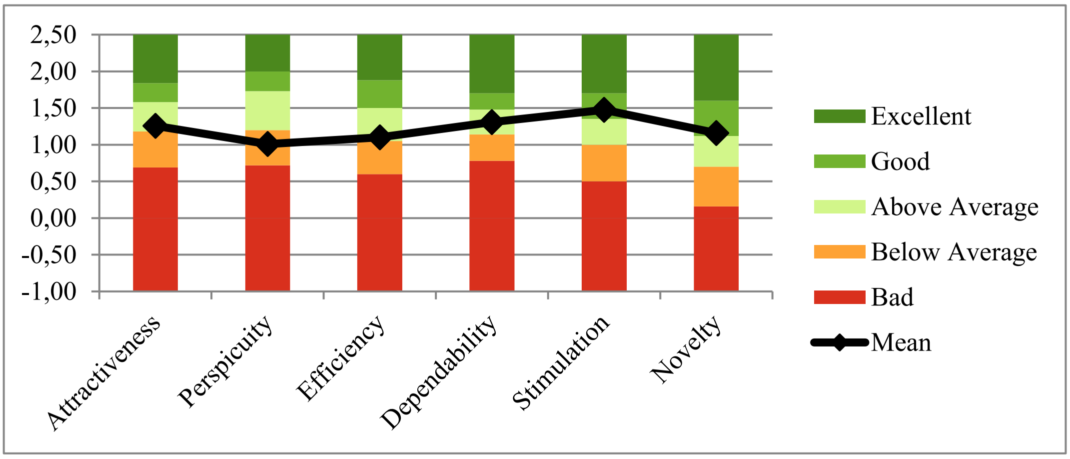

Figure 12. UEQ benchmark of the AR-based textbook in the first testing phase

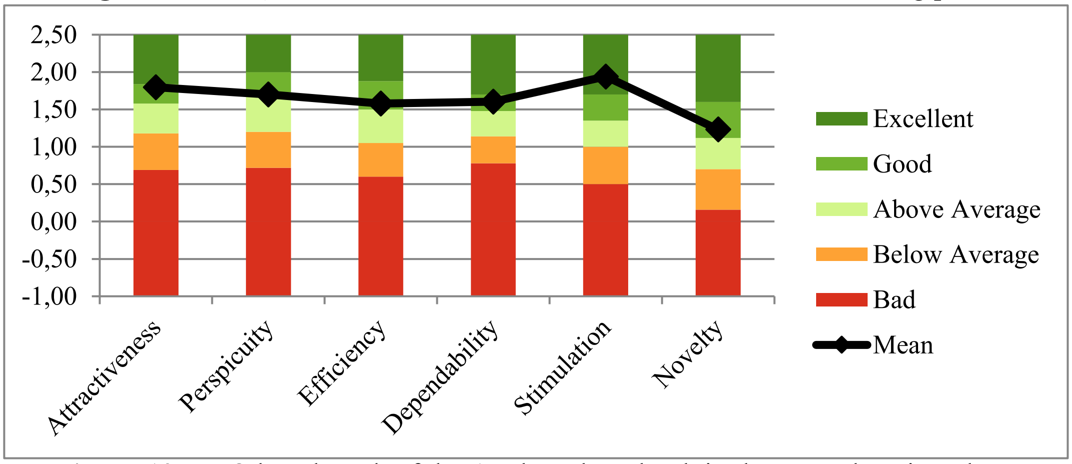

Figure 13. UEQ benchmark of the AR-based textbook in the second testing phase

The UEQ evaluation of the AR-based textbook revealed a consistent improvement in user experience from the first to the second testing phase. As illustrated in Figures 12 and 13, the initial evaluation demonstrated relatively high scores in the attractiveness and stimulation dimensions, whereas perspicuity and efficiency were rated lower. This pattern aligns with previous research on educational augmented reality, which indicates that augmented reality environments effectively promote engagement and novelty but often face challenges with usability and interaction clarity for novice users (Gräser et al., 2024; Ibáñez & Delgado-Kloos, 2018). This finding suggests that although augmented reality is inherently engaging, its pedagogical effectiveness is highly dependent on interface clarity and user guidance.

IV. DISCUSSION

The lower Perspicuity score observed in the initial evaluation suggests that users had difficulty understanding the core interactions of the augmented reality system, including marker scanning, three-dimensional object activation, and interface navigation. Prior studies have emphasized that insufficient onboarding can increase cognitive load and negatively affect early user experience in augmented reality environments (Hasan et al., 2025; Law & Heintz, 2021; Makransky & Mayer, 2022). In addition, the suboptimal Efficiency score indicates that system responsiveness, particularly in terms of marker detection time, three-dimensional model loading, and interface reaction, had not yet reached an optimal level. Such technical inefficiencies are known to degrade the overall user experience, especially in educational contexts that require stable, rapid interaction (Pratama et al., 2022; Bower et al., 2014). From a design perspective, these findings underline the importance of minimizing both cognitive and technical barriers during the early stages of augmented reality adoption.

Conversely, the Stimulation and Novelty dimensions were rated positively in the first evaluation, reflecting augmented reality content's capacity to create an engaging and motivating learning environment. Empirical evidence from recent meta-analyses confirms that augmented reality can significantly enhance learner motivation by providing interactive and visually concrete representations of abstract concepts (Pertiwi et al., 2025; Na & Yun, 2024; Garzón et al., 2019). These findings support the effectiveness of integrating augmented reality into the textbook's instructional design, particularly in facilitating conceptual understanding in physics.

To address the identified usability limitations, an iterative user-centered design framework was employed, encompassing problem identification, solution design, implementation, and re-evaluation. Key improvements included simplifying interaction workflows, integrating concise onboarding tutorials, optimizing marker recognition performance, and enhancing visual feedback during scanning activities. Furthermore, interface elements were refined to improve clarity and accessibility, consistent with established augmented reality usability guidelines (Law & Heintz, 2021; Sirakaya & Cakmak, 2018). These iterative refinements demonstrate the critical role of user-centered design in ensuring that augmented reality technology is not only innovative but also pedagogically effective.

The second UEQ evaluation demonstrated improvements across nearly all dimensions. Notably, Perspicuity and Efficiency showed substantial increases, indicating improved learnability and operational fluency. Attractiveness and Stimulation also increased, suggesting that improvements in usability did not reduce user engagement. This finding reinforces the principle that usability and engagement can be optimized simultaneously through careful design. The Dependability dimension showed moderate improvement, highlighting continuing challenges related to technical stability, which are characteristic of augmented reality applications that depend on camera and sensor accuracy (Singh & Ahmad, 2024). This indicates that although interface improvements can enhance user experience, hardware and system limitations remain important considerations in augmented reality implementation.

Overall, the improved UEQ results indicate that the AR-based textbook has been developed into a more usable and stable learning medium through iterative and data-driven refinement. Beyond the observed usability improvements, these findings offer important implications for future augmented reality textbook design in physics education. First, effective augmented reality integration requires a balance between engagement and usability so that interactive features support rather than overwhelm learners. Second, clear onboarding and intuitive interface design are essential to reduce cognitive load, particularly for first-time users. Third, augmented reality should be positioned not merely as a technological enhancement, but as a pedagogically integrated tool that supports conceptual understanding. Finally, attention to system performance and technical reliability is essential for sustainable classroom implementation. By addressing these aspects, AR-based textbooks demonstrate strong potential for scalable and effective use in diverse educational settings (Ibáñez & Delgado-Kloos, 2018; Garzón et al., 2019).

V. CONCLUSION AND SUGGESTION

This study demonstrates that the ARI-based physics textbook is feasible and user-friendly for supporting the learning of motion dynamics. Developed through a design thinking approach, the textbook aligns instructional objectives with user needs and integrates textbook content, student worksheets, and marker-based augmented reality features into a unified learning resource. Expert validation confirmed that the textbook met the required content and language standards, while the usability evaluation showed that the product was acceptable for classroom use. In addition, the UEQ results indicated improvements across all measured dimensions after iterative refinement, with stimulation and attractiveness showing particularly positive outcomes. These findings suggest that the ARI-based textbook can enhance student engagement and support the understanding of abstract physics concepts through interactive visualization.

Despite these positive findings, this study has several limitations. The evaluation was conducted within a limited educational context and focused primarily on feasibility, usability, and user experience, without examining learning outcomes through experimental or longitudinal designs. In addition, the implementation of the ARI-based textbook depends on technological factors such as smartphone capability, camera quality, and device availability, which may influence the consistency of use across different school settings. Therefore, future research is recommended to involve more diverse participants, apply experimental or longitudinal approaches, and further improve onboarding instructions, system performance, and cross-device compatibility. Nevertheless, this study contributes to the field of physics education by providing a user-centered model for integrating augmented reality into structured instructional materials, thereby extending its use beyond standalone applications and offering a practical direction for developing innovative, pedagogically meaningful, and technology-enhanced physics learning resources.

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