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THE EFFECT OF USING GEOGEBRA SOFTWARE FOR AUGMENTED REALITY VISUALIZATION TO TEACH PHYSICS IN HIGH SCHOOL

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Abstract. The primary objective of this research is to assess the impact of GeoGebra software, an instructional tool incorporating augmented reality and sensing technology, on both the academic achievement and the learning experience of pupils in the context of teaching physics. The study aims to gather insights from pupils regarding their perspectives on augmented reality. To achieve these goals, a mixed-method approach was utilized. The findings of this study suggest that learning environments incorporating augmented reality can be effective tools for teaching physics. Augmented reality provides a unique way to enhance the learning process by introducing visual and textual elements that can make abstract concepts more tangible and engaging for pupils. This technology can help pupils overcome their fear of physics, stimulate their curiosity, and make the subject matter more appealing. Additionally, the study highlights the potential of augmented reality to improve academic achievement, especially in areas where pupils struggle to grasp complex concepts. It can offer a more realistic and interactive learning experience compared to traditional classroom settings, which can lead to better comprehension and retention of physics principles. The use of augmented reality in physics education appears promising, and further research in this area could provide valuable insights into how to leverage technology to enhance the learning experience for pupils in various subjects. Pupils engaged in activities integrated with augmented reality displayed increased participation, greater comfort, and improved ability to address subject-related questions, heightened self-confidence, and achieved higher academic success in physics. Augmented reality should be viewed as a standalone learning environment for physics instruction and as a supplementary tool to enhance the traditional laboratory setting.

Key words: teaching physics, teaching methodology, high education, augmented reality, applications for teaching physics.

Introduction

Technology plays a pivotal role in aiding pupils' comprehension of real-world scenarios and issues by facilitating the visualization of the concepts being taught (Huba, 2016:39). The technological advancements of the past century, especially the widespread use of computers, have spurred rapid development and the creation of new technologies that effectively integrate computer-generated data into real-world environments. Augmented reality stands as a prime example of these innovative technologies (Baygin, 2016:112). In our experimental study, we define augmented reality as the fusion of the virtual and the real, offering real-time interaction and three-dimensional elements. Augmented reality enriches the user's perception of the actual environment by providing computer-generated virtual data that enhances their understanding. This technology serves as a powerful tool for bridging the gap between abstract concepts and tangible real-world applications, thereby facilitating learning and comprehension (Demartini, 2017:157). Augmented reality has witnessed a significant increase in popularity and accessibility, particularly since the 2000s when a wider range of code libraries became available. The momentum of augmented reality technology notably surged in 2011, and it has since continued to advance and find applications across various fields. Augmented reality implementations leverage the real world as their foundation, transcending constraints of space and time (Carroll, 2019:97). They seamlessly blend elements of the physical and virtual realms to enhance the learning experience. One notable feature is the three-dimensionality of objects visualized in augmented reality, which captures users' attention and generates a heightened level of interest and engagement.

This technology has proven to be a versatile and valuable tool across diverse domains. Educational augmented reality applications have the potential to extend pupils' attention spans on a subject, consequently enhancing their levels of academic achievement (Fisk, 2016:319). The three-dimensionality inherent in augmented reality activities plays a pivotal role in helping pupils solidify their understanding of abstract concepts such as position, angle, rotation, and revolution. Augmented reality also empowers pupils to engage in scientific thinking and encourages them to formulate and test hypotheses. This active involvement in the learning process fosters a deeper understanding of the subject matter and promotes critical thinking skills, ultimately leading to a more immersive and effective educational experience (Kreijns, 2013:217). Physics is often regarded as a challenging subject in the literature, primarily because pupils face difficulties in explaining the phenomena of the world around them, comprehending concepts that are entirely new to them, connecting these concepts to everyday life, and making theoretical concepts more tangible. Much of the existing literature on physics education is centered around strategies and approaches to effectively teach this complex subject, recognizing the need to address these challenges and enhance pupils' understanding and engagement in physics. To achieve this objective, it is essential for pupils to engage in experiential learning, approach physics with the curiosity and questioning mindset of a scientist, and actively participate in the learning process.

Augmented reality, as an experiential learning tool, is recognized for its capacity to facilitate effective information and skill acquisition among pupils. It encourages pupils to immerse themselves in hands-on experiences, develop scientific thinking skills, and take an active role in their own learning journey. This combination of experiential learning and augmented reality can greatly contribute to enhancing pupils' understanding and proficiency in physics (Dror, 2008:215). The primary objective of the present study is to examine how instructional material integrating augmented reality and sensing technology impacts the academic achievement of pupils in the field of physics. The researchers hypothesize that an augmented reality-learning environment has the potential to enhance pupils' academic performance. By conducting this study, they aim to contribute valuable insights to the existing body of literature in the field of education, specifically regarding the benefits of augmented reality in improving pupils' academic achievement in physics. In addition to its primary objectives, the current study provides pupils with a range of augmented reality learning experiences that blend virtual elements seamlessly with the real-world environment (Martin, 2011:1893). The study not only explores the impact of augmented reality on academic achievement but also offers information about the fundamental characteristics of augmented reality technology and its diverse applications in different domains. This comprehensive approach allows pupils to gain practical insights into the potential of augmented reality as an educational tool and its relevance in various contexts. Furthermore, the study offers valuable guidance on structuring lessons that emphasize inquiry-based learning and practical class environments. This research stands out as one of the relatively rare studies that focus on teaching physics using augmented reality in a three-dimensional context. Additionally, it incorporates the use of a microcontroller and a triaxial magnetic field sensor in classroom activities, marking it as an innovative and pioneering contribution to the field of physics education (Bronack, 2011:117).

Literature review

Augmented reality is indeed considered a relatively new and highly significant technology with broad applications across various fields, including education. Its capacity to enable pupils to explore and discover information in an interactive and immersive manner is of particular importance. Additionally, the integration of sensors into augmented reality environments enhances the learning experience by aiding pupils in improving their psychomotor skills and actively engaging their sensory organs in the learning process (Milgram, 1994:292). This technology has the potential to revolutionize educational practices by making learning more engaging, interactive, and effective.. The active engagement of pupils in applying these skills within augmented reality environments can have a positive impact on their personal learning experiences. Because augmented reality experiments are conducted in real time and offer interactivity, pupils are encouraged to engage in critical self-analysis (Azuma, 1997:385).

This self-analysis fosters a deeper level of understanding, encourages pupils to question and reflect on their own learning, and ultimately contributes to a more enriched and self-driven educational journey.

Indeed, careful consideration of the choice of objects to be presented virtually within an augmented reality environment and the meaningfulness of these changes to learners is crucial. Such considerations play a pivotal role in enhancing the effectiveness of augmented reality implementations. By selecting relevant and contextually meaningful virtual elements, educators can ensure that the augmented reality experience aligns with the learning objectives and provides pupils with valuable insights and experiences that reinforce their understanding of the subject matter. Thoughtful design and integration of virtual objects contribute to the overall success and impact of augmented reality in education. In the past decade, there has been a notable surge in research focused on augmented reality environments. This trend can be attributed to the recognition that augmented reality has the potential to enhance pupils' interest, motivation, and overall learning experiences (Höllerer, 2004:421). Researchers and educators alike have increasingly explored the benefits of augmented reality as a means to engage pupils, make learning more enjoyable, and improve the overall quality of education. This growing body of research reflects the evolving landscape of educational technology and its impact on modern pedagogy.

Moreover, augmented reality provides an alternative learning environment that serves as a bridge between the virtual and the real world. It facilitates the transfer of information and skills acquired within a virtual context to real-world scenarios. Augmented reality effectively bridges the gap between concrete, tangible information and abstract concepts, making it easier for pupils to grasp complex ideas (Kaufmann, 2003:97). Additionally, it enables pupils to develop spatial intuition, enhancing their ability to understand and navigate the physical world more effectively. These multifaceted benefits further underscore the significance of augmented reality in education. The literature consistently highlights that augmented reality learning environments are conducive to constructivist learning, wherein pupils actively discover information and construct their knowledge. Additionally, research has underscored that pupils in these environments enhance their psychomotor skills through active engagement and participation. Furthermore, the sensory organs of pupils become more activated as they interact with augmented reality, contributing to a more immersive and comprehensive learning experience (Zhou, 2008:202). These findings collectively demonstrate the educational value and benefits of augmented reality as a tool for fostering active and experiential learning. Augmented reality environments, being participatory activities, have the capacity to significantly enhance pupils' personal learning experiences. This aligns with the idea that educational environments leveraging augmented reality can have a positive impact on pupils' academic achievement.

Augmented reality implementations have the potential to make learning more accessible and effective, particularly in tackling relatively challenging subjects and courses. The active and immersive nature of augmented reality contributes to a deeper understanding and engagement, ultimately leading to improved academic outcomes across a range of subjects. Indeed, physics, a topic commonly covered in high school physics teaching, is often perceived as challenging pupils to grasp (Adams, 2006:101).

Table 1 – List of factors that contribute to the difficulties encountered by pupils in physics

№	Factor	Description
1	Lack of Real-World Association	Difficulty in associating physics concepts with everyday life scenarios can make it abstract and less relatable.
2	Theoretical Nature:	Physics involves theoretical concepts that may not have immediate practical applications, making it harder for pupils to visualize and understand.
3	Complex Mathematical Procedures	The subject often requires the application of complex mathematical procedures, which can be daunting for pupils.
4	Abstract Concepts	Physics introduces numerous abstract concepts that may not align with pupils' prior experiences, making it challenging to form mental models.

These challenges highlight the need for effective teaching strategies and tools, such as augmented reality, to bridge the gap between abstract concepts and real-world applications and to engage pupils more actively in the learning process (Aviandari, 2022:41-51). As a result of the learning challenges associated with physics, many pupils have inadequate knowledge of the topic, with some having learned very little or nothing about it. This issue extends beyond high school, as even college-level pupils may possess insufficient prior knowledge of physics. However, utilizing augmented reality learning environments can be instrumental in addressing these educational hurdles (Arymbekov, 2022:128-141). Augmented reality provides a dynamic and immersive platform for teaching complex subjects like physics. By offering interactive visualizations and experiential learning opportunities, augmented reality can make abstract concepts more tangible and engaging for pupils, ultimately helping to bridge the knowledge gap and enhance their understanding of physics (Arymbekov, 2023:52-55). It is worth noting that there is limited published research in the literature regarding the application of augmented reality in teaching physics as a subject.

However, your study aims to fill this gap by utilizing an augmented reality environment to teach various aspects of physics (Arymbekov, 2023:19–24). The topics covered include magnetic force, magnetic field lines, the Earth's magnetic field, and the right-hand rule. This innovative approach holds the potential to contribute valuable insights and strategies for using augmented reality as an effective educational tool in the field of physics. In our study, we employed visual representations, or visual figures, to illustrate magnetic field lines. These visual figures were part of augmented reality implementations that incorporated objects corresponding to the concepts being taught. Furthermore, these augmented reality implementations demonstrated how the magnetic field underwent changes due to the interactions and forces exerted by these objects on each other. This approach effectively merged theoretical concepts with interactive, visual, and real-time representations, enhancing the learning experience for pupils studying physics (Arymbekov, 2023:76). To facilitate learning, we introduced these augmented reality implementations into the classroom environment. Additionally, we developed a specific learning object that could be utilized within augmented reality environments to educate pupils about the concept of magnetic field poles.

In parallel, we also carried out foundational implementations related to physics in mobile environments. These combined efforts aimed to offer a diverse range of learning experiences and materials, ensuring that pupils could engage with physics through augmented reality both in the classroom and on mobile platforms. Furthermore, we applied the principles of physics and used three-dimensional simulations to visualize magnetic field behaviors (Arymbekov, 2023:150). This approach allowed us to gather data and create step-by-step visualizations of magnetic field lines on a vector structure, employing our unique methods.

By doing so, we aimed to provide pupils with a comprehensive and interactive understanding of magnetic field concepts, enhancing their ability to grasp the complex behaviors of magnetic fields in a three-dimensional context. To further enrich the learning experience, we leveraged mobile hardware to enhance the visualization of magnetic field lines within an augmented reality book focused on physics (Yuen, 2011:119). This innovative approach aimed to make the subject more accessible and engaging for pupils. As demonstrated, there has been noteworthy and intriguing research conducted in the area of teaching physics through augmented reality. These efforts are contributing to the development of effective and immersive educational tools that can significantly benefit pupils' understanding of complex scientific concepts. The current study sets itself apart from previous research by its specific focus on visualizing the strength and direction of a magnetic field within an experimental context.

Additionally, the study goes a step further by developing instructional materials that allow pupils to actively use and control within the augmented reality environment. These unique aspects of the research are expected to make a substantial contribution to the existing literature, offering new insights and practical tools for teaching physics effectively through augmented reality (Dunleavy, 2009:22).

Methodology

Table 2 – List of three primary research questions for experiments

№	Questions	Explanation
1	How does learning physics using augmented reality instructional material impact pupils' academic achievement?	This question explores the effect of augmented reality on pupils' academic performance in the subject of physics.
2	How do learning activities change when physics is taught using augmented reality instructional material?	This question investigates the shifts and enhancements in the learning activities and experiences of pupils when augmented reality is incorporated into the teaching of physics.
3	What are the perspectives and insights of pupils regarding augmented reality?	This question delves into pupils' perceptions, opinions, and insights about augmented reality as an educational tool, providing valuable feedback and understanding of their experiences with this technology.

These research questions collectively contribute to a comprehensive examination of the impact and effectiveness of augmented reality in the context of teaching physics (Kye, 2008:14).

The study involved a sample of 791 11th-grade pupils who were enrolled in physics classes at a medium-sized high school situated in the Ili district of Kazakhstan. To develop and refine the achievement test used in the study, a pilot test was administered to 793 pupils drawn from twelve different schools. This rigorous approach to piloting and testing ensures the validity and reliability of the assessment instrument used in the research. In the primary phase of the study, a total of thirty-three physics classes were chosen to participate. Among these classes, there were two control groups, each consisting of 260 pupils, and one experimental group with 260 pupils. The selection of these three classes was predicated on the fact that all three classes were taught by the same teacher. This uniformity in teaching allowed for more controlled and comparable conditions when implementing the study's experimental and control groups. Table 1 provides comprehensive information regarding the sample and the research procedures. In the case of the two control groups, pupils received instruction either in a traditional classroom setting or in a conventional laboratory environment. It is important to note that the literature review has indicated that some teachers opt not to use laboratory facilities for a variety of reasons.

As a result, many lessons are conducted in the standard classroom environment rather than in specialized laboratory settings. Hence, the first control group received instruction in a regular classroom environment. However, it is worth noting that laboratory practices were still integrated into the teaching and learning process, aligning with the requirements outlined in the 11th-grade Physics curriculum established by the Kazakh Ministry of Education. This approach ensured that the curriculum's stipulated activities were incorporated into the educational experience of the first control group, even within the confines of a standard classroom. Considering that a substantial portion of physics instruction involves laboratory activities, the second control group received their lessons in a traditional laboratory environment. Given that the study's objective was to make a comparison between these two distinct learning environments (traditional classroom vs. classic laboratory) and an augmented reality-assisted laboratory environment, where newly developed augmented reality instructional materials were employed, all three groups (first control, second control, and experimental) were included in the study. This inclusive approach allowed for a comprehensive examination of the impact of these different instructional settings on pupils' learning experiences and outcomes. (Pence, 2010:145).

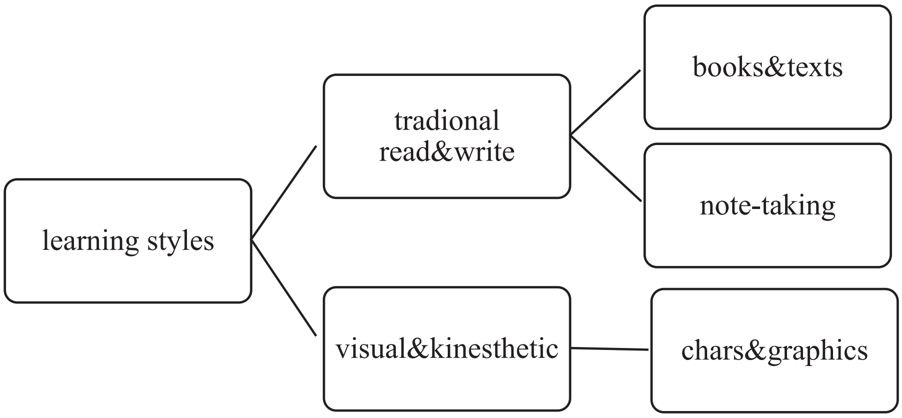

Figure 1 – Research design and implementation. Procedures

To align with the study's objectives, an embedded mixed-methods approach was adopted. In the quantitative component of the study, a quasi-experimental design was employed, which included both pre-test and post-test assessments. The primary dependent variable under investigation was academic achievement, while the three distinct learning environments served as the independent variables. The aim was to examine the impact of these different learning environments on the dependent variable of academic achievement through quantitative analysis. The study encompassed three distinct learning environments: the traditional classroom, the classic laboratory, and an augmented reality-assisted laboratory. Alongside the pre-test and post-test assessments, the research incorporated qualitative data collection methods, including researcher observations and interviews. These qualitative approaches were designed to provide additional insights and a deeper understanding of the pupils' learning experiences within each of the three environments, complementing the quantitative analysis of academic achievement.

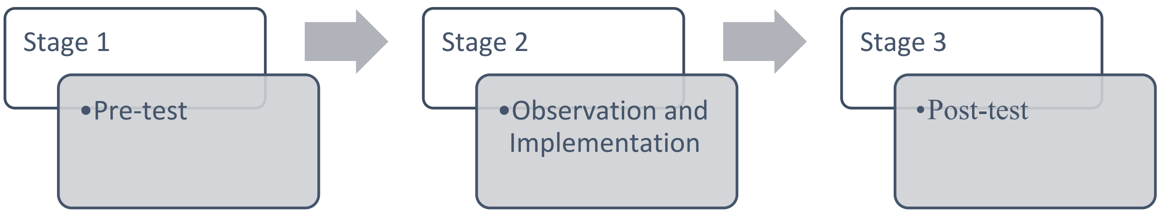

Figure 2 – Research design and implementation. Procedures of experiment

The study groups were chosen through a random selection process. Figure 1 outlines the research design and the steps taken to execute it. The primary stages of the study encompassed a thorough review of the existing literature, a needs analysis, the creation of instructional material using GeoGebra, piloting the material, carrying out the actual implementation of the study, and the subsequent analysis of the data collected. This systematic approach was designed to ensure the study's integrity and rigor throughout its execution. The pilot testing phase primarily aimed to assess the validity and reliability of the instructional material. This phase involved the participation of two experienced teachers, each with more than 10 years of professional experience in teaching. These teachers had extensive experience in utilizing various devices in their laboratory activities. The interviews conducted during this phase focused on conducting a needs analysis and comparing the devices readily available at the school with the newly developed instructional material designed for teaching the topic of physics (Laal, 2013:1437).

This rigorous testing and evaluation ensured that the instructional material was sound and effective before its implementation in the main study. The first control group received physics instruction in a regular classroom setting, while the second control group was taught in a physics laboratory. The experimental group, however, was also taught in a physics laboratory, but their instruction incorporated the use of augmented reality instructional material. In all three groups, an inquiry-based learning approach was employed to convey the necessary knowledge to pupils regarding the topic of physics. To assess the impact of these different instructional approaches, an achievement test focused on physics was administered to all three groups as both a pre-test and a post-test, allowing for a comparison of learning outcomes before and after the interventions. The concluding phase of the study incorporated qualitative research methods, namely interviews and observation. Interviews were conducted with the teacher, who taught all three classes, as well as with three pupils from the experimental group and two pupils from each of the control groups. The purpose of these interviews was to gather insights and perspectives from both the teacher and the pupils regarding their experiences with the different instructional implementations and learning environments.

This qualitative data collection aimed to provide valuable context and qualitative information to complement the quantitative findings of the study (Doymu, 2007:1857). During the interviews, each participant was tasked with elucidating the drawbacks they perceived in their respective learning environments, as well as assessing the extent to which the learning environment facilitated the attainment of the learning objectives outlined in the physics curriculum. The goal was to discern any disparities in the perspectives of the pupils regarding their learning environments. Additionally, the researcher conducted observations in all three learning environments to gauge their contributions. The observations concentrated on the level of interest exhibited by the pupils in their lessons and encompassed an assessment of their behaviors and attitudes within these environments. These combined qualitative approaches aimed to provide a comprehensive understanding of the pupils' and teacher's perspectives on the learning experiences. Data gathered from the interviews were subjected to analysis, with a focus on the responses provided by the pupils to open-ended questions. Some of these responses are featured in the presentation of the study's results in the form of quotations from the participants.

Additionally, summarized data from the researcher's observations were included as supplementary findings. The integration of both datasets served to enhance the overall reliability of the study by offering multiple perspectives and sources of information on the learning environments and their impact on pupils' experiences and outcomes.

Table 3 – Experiment representation of the sample and procedures

№	Study Type	Group type	Number of Pupils	Gender balance	Age range
1	Augmented reality Laboratory	Experimental	260	130/130	15-17
2	Classroom	Control	260	130/130	15-17
3	Traditional Laboratory	Control	260	130/130	15-17

To facilitate the study's execution at the chosen high school, a formal written application was submitted to the Ministry of Education. Necessary permissions were sought and obtained for each phase of the study, including the various implementations, the administration of achievement tests, and the utilization of data collection instruments (Gokhale, 2013:57). This protocol ensured that the study adhered to all necessary ethical and procedural requirements for conducting research within the educational context. The data collection instruments employed in the study comprised an achievement test (administered both as a pre-test and a post-test), researcher observations, and interviews with both the teacher and the pupils. This section also provides insights into the design of the instructional material. The achievement test was collaboratively developed by the researcher and two physics teachers from the school where the study was conducted. It consisted of 30 multiple-choice questions designed to assess pupil achievement in the area of physics. The interviews were conducted to gather the perspectives of the teacher and pupils regarding the impact of the different learning environments on pupil learning and motivation. Additionally, interviewees were invited to provide feedback on the learning activities and equipment employed.

Researcher observations were conducted using a structured observation form tailored to identify reflections of the learning environments. This form facilitated the systematic collection of data about pupil engagement, behavior, and attitudes in each of the three learning settings. These data collection instruments collectively contributed to the study's comprehensive assessment of the effects of different learning environments on pupil learning outcomes and experiences. The 11th-grade physics curriculum in Kazakhstan outlines several learning outcomes related to the topic of physics.

Table 4 – List of the learning outcomes

№	Categories	Description
1	Explaining Magnet Attraction and Repulsion	Pupils are expected to be able to explain the phenomena of attraction and repulsion between magnets, using the concept of magnetic field area.
2	Discovering Magnetic Fields	Pupils should discover and understand that current-carrying circles and solenoids generate magnetic fields.
3	Understanding Magnetic Force	The curriculum requires pupils to comprehend the magnetic force that exists between two current-carrying conducting wires.
4	Observing and Explaining Magnetic Effects on Current-Carrying Wires	Pupils are expected to observe and provide explanations for the effects of the force exerted on a current-carrying rectangular conducting wire frame when it is placed in a magnetic field. These learning outcomes serve as educational goals and objectives for pupils studying physics in the 11th-grade physics curriculum, providing a framework for their understanding of this topic.

Table 5 – Validation process to ensure the quality and effectiveness of the achievement test used in the study

№	Steps	Explanations of steps
1	Expert Review	A faculty member who specializes in the field of physics education was invited to evaluate the content validity and clarity of the achievement test. Their expertise helped assess whether the test adequately covered the intended content and whether the questions were clear and appropriate.
2	Teacher Review	Two physics teachers, with expertise in the subject matter, were also involved in reviewing the test. Their input was valuable in ensuring that the questions aligned with the curriculum and were suitable for the intended grade level.
3	Pilot Testing	The achievement test was then piloted with a larger group of 793 pupils from two different schools. This pilot test served multiple purposes, including: Identifying any difficulties that pupils might encounter while understanding the test questions and answer choices. Evaluating the time it took for pupils to complete the entire test. The feedback and data collected during the pilot testing phase likely led to refinements and adjustments to the test items to enhance its effectiveness and clarity.

This thorough validation process helps ensure that the achievement test used in the study accurately assesses pupils' knowledge and aligns with the educational objectives of the research.

Table 6 – The reliability of the achievement test was assessed through a comprehensive item analysis, and several steps were taken to refine the test:

№	Type	Explanation
1	Item Analysis	Each test item was subjected to item analysis, which involves evaluating the performance of individual items. During this analysis, the researchers likely examined statistics such as item difficulty (the percentage of pupils who answered the item correctly) and item discrimination (the extent to which the item distinguishes between high and low achievers).
2	Item Exclusion	Based on the results of the item analysis, three questions were identified as having insufficient discrimination indices. These questions were subsequently excluded from the final version of the achievement test. This step aimed to improve the overall quality of the test.

3	Finalized Achievement Test	After removing the problematic items, the achievement test was revised to contain a total of 17 multiple-choice questions.
4	Reliability Measurement	To assess the test's reliability, the researchers likely calculated the Spearman-Brown reliability coefficient. In this case, the coefficient was found to be 0.87 for the finalized version of the achievement test. This high coefficient indicates a strong degree of reliability, suggesting that the test consistently measures what it is intended to measure.
5	Pre-Test and Post-Test	The final version of the achievement test was administered to the pupils in all three study groups both before (pre-test) and after (post-test) the experimental implementation. This allowed for the assessment of changes in pupil performance and learning outcomes as a result of the different learning environments.

By conducting a rigorous item analysis and ensuring the reliability of the test, the researchers aimed to obtain valid and consistent data to measure the impact of the instructional interventions on pupil achievement.

The interviews in this study were carefully planned and conducted to ensure that they effectively addressed the research questions and provided valuable insights.

Table 7 – List of key details about the interview process

№	Phase	Process explanation
1	Question Preparation	The interview questions were thoughtfully composed to align with the specific research questions of the study. This ensured that the information gathered through interviews would be relevant and informative for the research objectives.
2	Participant Informed Consent	Prior to the interviews, all participants, including the teacher and seven pupils, were provided with clear information about the purpose of the interviews, how their responses would be used in the study and the importance of providing honest and sincere answers. This step aimed to secure informed consent and cooperation from the participants.
3	External Review	To enhance the clarity and effectiveness of the interview questions, they were reviewed by a faculty member who specialized in the relevant field. This external review likely helped refine the questions.
4	Voluntary Participation	The participation of the interviewees, both the teacher and pupils, was voluntary. This approach respects the autonomy of the participants and ensures that they were willing to share their perspectives willingly.
5	Semistructured Format	Semistructured interview forms were employed, indicating that while there was a predefined set of questions, there was also room for open-ended discussion and exploration of the topics. This format allows for richer qualitative data collection.
6	Audio Recording	All interviews were audio-recorded, which is a common practice in qualitative research. This recording method helps capture the participants' responses accurately and allows for later transcription and analysis.
7	Interview Setting	The interviews were conducted one-on-one in a physics laboratory. This setting likely provided a comfortable and appropriate environment for discussing topics related to the study.
8	Duration	On average, each interview lasted approximately 30 minutes. This duration suggests that the interviews were efficiently conducted, allowing participants to share their insights without excessive time demands.

Overall, these careful considerations and procedures in the interview process contribute to the credibility and reliability of the qualitative data gathered in the study.

The researcher observations in this study were conducted with careful consideration for ethical and practical factors.

Table 8 – List of key details about the researcher observation process

№	Method	Explanation of methods
1	Recording Method	Unlike the interviews, the researcher observations were not audio-recorded or video-recorded. This decision was made because neither the teacher who conducted the experimental implementation nor any of the pupils agreed to such recording. This approach respects the preferences and consent of the participants.

2	Purpose of Observations	The primary purposes of the researcher observations were twofold: to assess the consistency of the answers provided in the interviews and to identify any incidents or events during the experimental implementation that might not have been mentioned in the interviews. This dual focus provides a comprehensive view of the study's context.
3	Note-Taking	Instead of audio-visual recording, the researcher opted for taking written notes during the lessons. These notes were then organized and summarized. This method was chosen to avoid potential negative effects on both the teacher and pupils that could arise from being recorded audio-visually. Note-taking allows for a discreet and unobtrusive observation process.
4	Nonparticipant Observer	The researcher played the role of a nonparticipant observer during the lessons. This means that the observations were conducted without actively participating in the lessons, ensuring minimal disruption to the teaching and learning process.
5	Structured Observation Form	To maintain consistency and structure in the observations, the researcher, along with a faculty member, developed a structured observation form. This form included predefined categories for observations, such as asking questions, replying, confirming, and giving examples. This structure helps categorize and analyze the observed behaviors and interactions.
6	Overall	these considerations in the researcher observation process reflect a balanced approach that respects the privacy and preferences of the participants while still providing valuable insights and data for the study's objectives.

The development of the instructional material for this study was guided by the specific learning objectives outlined in the 11th-grade Kazakh high school physics curriculum, with a focus on the topic of physics. Physics is traditionally taught using various instructional methods, including simple laboratory equipment, simulations, animations, and data loggers.

Table 9 – List of aims to design instructional materials that align with these curriculum goals and provide an for pupils

№	Design instructional materials	Effective learning experience
1	Curriculum Alignment	The researchers reviewed the curriculum guidelines and identified the key learning attainments related to physics. These learning objectives served as the foundation for the development of instructional content.
2	Content Creation	Based on the curriculum objectives, the researchers created content that covered the necessary physics concepts. This content likely included explanations, diagrams, visual aids, and interactive elements designed to enhance pupil understanding.
3	Pedagogical Approach	The instructional material was likely designed with a specific pedagogical approach in mind. Given the nature of the study, an inquiry-based learning approach was mentioned, indicating that the material likely encouraged pupils to explore concepts through hands-on activities and critical thinking.
4	Integration of Augmented Reality	To ensure the instructional material's relevance and effectiveness, it likely involved the following steps:
5	Instructional material	The key innovation in this study was the incorporation of augmented reality technology into the instructional material. This likely involved creating or selecting 3D models, simulations, or visualizations that could be overlaid onto the real-world environment through augmented reality.
6	Pilot Testing	Before the actual study, the instructional material was likely piloted to assess its effectiveness, clarity, and alignment with the curriculum. This pilot testing phase may have involved physics teachers and pupils to gather feedback and make necessary adjustments.
7	Teacher Training	If the study involved a teacher implementing the instructional material, the teacher may have received training on how to use the augmented reality technology and integrate it into their teaching.
8	Data Collection Instruments	As part of the study's design, data collection instruments, including achievement tests and interviews, were likely developed to evaluate the impact of the instructional material on pupil learning and experiences.
9	General	The development of the instructional material was a critical aspect of the study, as it aimed to leverage augmented reality technology to enhance the teaching and learning of physics in the high school physics curriculum. The alignment with curriculum objectives and the use of innovative technology were key factors in its design.

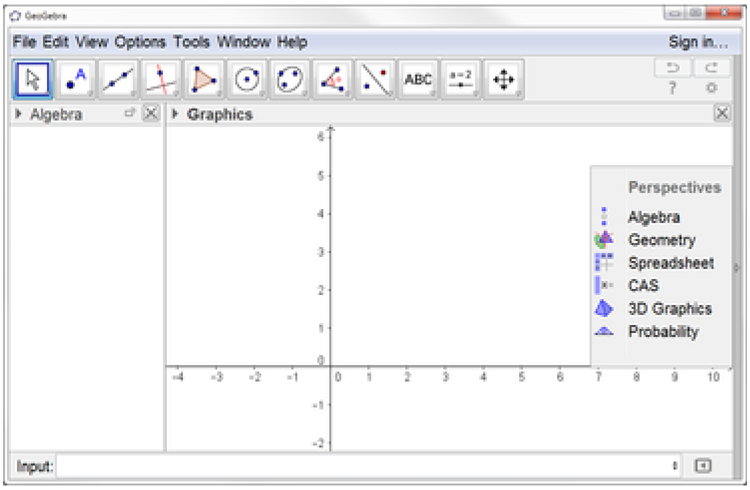

Figure 3 – Research design and implementation procedures

In this study, an instructional material based on GeoGebra was developed to teach physics effectively, especially when hardware supporting augmented reality was unavailable. The development process followed Analysis, Evaluation model, which is a widely used instructional system design model.

Table 10 – List of the development process in experiments

№	Phase Type	Explanation
1	Analysis Phase	During this phase, the researchers conducted a comprehensive review of the literature to gain insights into teaching physics effectively. The aim was to identify the specific needs and requirements for teaching this subject. This phase helped establish the foundation for the instructional material.
2	Design Phase	In the design phase, the focus was on creating the content for the instructional material. This likely involved breaking down the subject matter into manageable units or modules, determining the sequence of instruction, and designing the visual elements to support learning. The design also included the analysis of sample tools and the creation of a user-friendly interface.
3	Development Phase	The development phase involved creating the actual instructional material based on the design specifications. This likely included programming or creating interactive elements within the GeoGebra software. The material was developed in alignment with the identified needs and the content design from the previous phases.
4	Implementation Phase	During this phase, the developed instructional material was pilot-tested. This involved testing the material with a group of pupils to assess its effectiveness, usability, and any potential issues. Feedback from this pilot test may have informed further refinements to the material.
5	Evaluation Phase	The final phase involved evaluating the instructional material's effectiveness in teaching physics. This evaluation likely considered pupil performance, engagement, and feedback. The material's impact on pupil learning outcomes and experiences was a key aspect of this evaluation.

Figure 3 was mentioned as presenting the software of the instructional material. This likely includes a visual representation of the GeoGebra-based material, illustrating how it interacts with pupils and facilitates the teaching and learning of physics. The development of the instructional material was a systematic and iterative process designed to address the specific challenges of teaching physics, especially when AR hardware was not available. The use of GeoGebra as a platform for visualizing learning attainments in this subject demonstrates the innovative approach taken in this study.

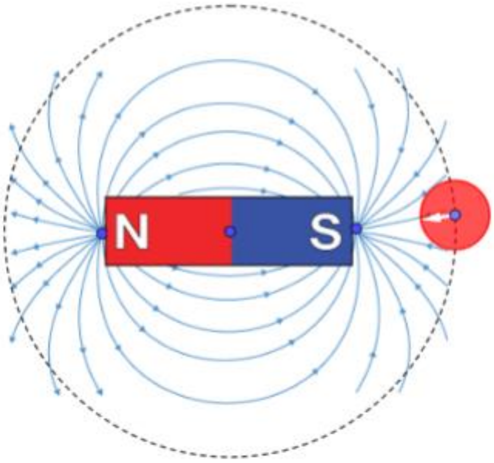

Figure 4 – Visualization magnetic in GeoGebra

Table 11 – The finalized version of GeoGebra used in the study exhibited several key characteristics and functionalities

№	Subject of Types	Explanation
1	Direction and Strength of the Magnetic Field	This feature allowed the visualization of the magnetic field, providing a clear representation of its direction and strength. Pupils could observe and interact with this virtual representation.
2	Components of the Magnetic Field	GeoGebra enabled exploration of the magnetic field's components along its x, y, and z axes. This likely provided a three-dimensional view of the magnetic field, enhancing pupils' understanding.
3	Photograph Function	Users had the ability to capture an image of the augmented reality environment as a .jpg file. This feature could be useful for documenting observations or results during learning activities.
4	Inactive Procedure	The "inactive procedure" likely allowed users to temporarily disable or ignore the magnetic field in the environment. This functionality could be valuable for isolating specific aspects of the learning experience.
5	Axis Procedure	Components of the magnetic field could be incorporated into the environment at any time. This feature may have allowed for dynamic adjustments and interactions with the virtual magnetic field.
6	Precise Measurement	GeoGebra offered precise measurement capabilities, allowing users to measure and analyze the effects of the magnetic field. Even subtle changes or measurements could be made, contributing to a detailed understanding of the subject matter.

These characteristics collectively enhanced the instructional material's capabilities, making it a valuable tool for teaching physics. By providing a dynamic and interactive virtual environment for exploring magnetic fields, GeoGebra likely contributed to pupils' engagement and comprehension of the topic. The design and development of the instructional material in GeoGebra for teaching physics through augmented reality involved a comprehensive process that adhered to various principles and criteria for effective augmented reality learning environments.

Table 12 – List of key points regarding the instructional material's design and features

№	Stage	Explanations
1	Reference to Augmented Reality Properties	The instructional material in GeoGebra was intentionally designed to leverage the unique properties of augmented reality. It aimed to create an immersive and interactive learning environment that aligned with the characteristics of augmented reality.
2	Selection of Subjects for Augmented Reality	The choice of physics as the subject matter for augmented reality instruction was based on thoughtful considerations. Physics likely offered rich opportunities for visualization and interactivity, enhancing the learning experience.

3	Scenario Design	The instructional material followed a scenario-based approach, allowing pupils to engage with real-world scenarios and applications related to physics. This likely provided context and relevance to the learning process.
4	Stages of Augmented Reality Environment Creation	The instructional material's design process followed established stages for creating augmented reality environments. This systematic approach likely contributed to its effectiveness.
5	Criteria for Successful Augmented Reality Learning Environments	The design of GeoGebra met specific criteria set by the researchers for successful augmented reality learning environments. These criteria likely ensured that the material aligned with the intended learning outcomes and instructional goals.
6	Interactive Features	GeoGebra incorporated various interactive features, such as the ability to take photographs, explore magnetic field axes (x, y, and z), temporarily ignore the magnetic field, and perform precise measurements even in areas with slight magnetic field effects. These features likely fostered engagement and active exploration.
7	Inquiry-Based Learning Approach	The activities within the instructional material were supported by an inquiry-based learning approach. This approach encouraged pupils to hypothesize, collect data, test hypotheses, evaluate results, and collaborate with peers. It likely promoted higher-level thinking skills, including analysis, synthesis, and evaluation.
8	Calibration and Validation	GeoGebra was subjected to calibration and validation processes, comparing its measurements and features with established magnetic field measurement tools like the Gauss/Tesla Meter, Magnetics Electro, MFS, and Mg-EL. This likely ensured the accuracy and reliability of the instructional material.

Overall, the design and development of the instructional material in GeoGebra appear to have been meticulously executed, considering both pedagogical principles and technological capabilities. The integration of augmented reality features likely enhanced the learning experience for pupils studying physics.

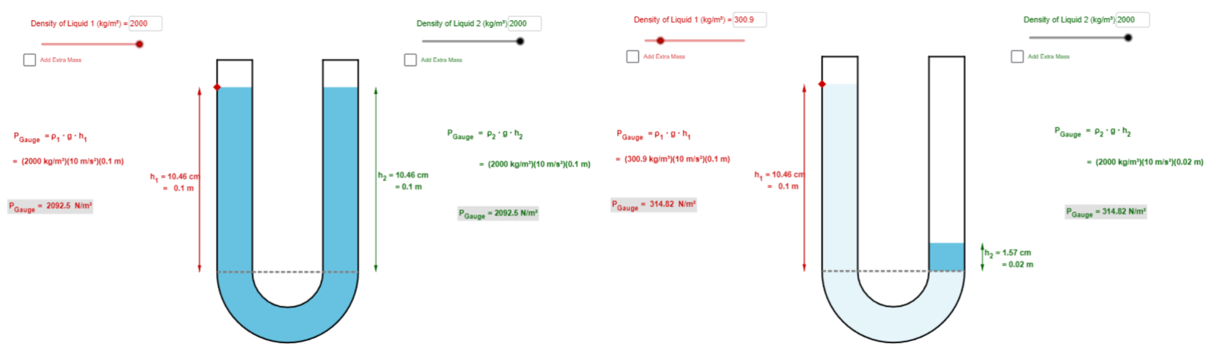

Figure 5 – Physics study materials in GeoGebra user interface.

In this section, the data collection instruments and the methods used for data analysis are outlined. The data collection process involved three main components: the Kazakhstani General National Test in-class researcher observation, and researcher interviews with both the teacher and 30 pupils.

Table 13 – Data collection instruments and the methods

№	**Collection methods**	**Application**
1	Kazakhstani General National Test	The test served as a quantitative data collection instrument. It was administered to all three groups of pupils, both as a pre-test before the instructional interventions and as a post-test after the interventions were completed. The test consisted of 17 multiple-choice questions designed to assess pupils' understanding of physics

2	In-Class Researcher Observation	In-class researcher observations were conducted to gather qualitative data about the pupils' behaviors, engagement levels, and attitudes in the different learning environments. These observations were systematic and focused on specific aspects, such as how interested the pupils appeared in the lessons, their behaviors, and their attitudes during the learning activities. Researchers took notes during the observations to document their observations.
3	Researcher Interviews	Interviews were conducted with both the teacher who conducted the instructional interventions and a selected group of seven pupils. These interviews were semi-structured and aimed to capture the perspectives and insights of the participants regarding the impact of the different learning environments on pupil learning and motivation. The interviews were audio-recorded and later transcribed for analysis.
4	Data Analysis	Data collected through these instruments were analyzed using a mixed-methods approach, combining both quantitative and qualitative data:
5	Quantitative Data Analysis	The quantitative data obtained from the Kazakhstani general national test, which included pre-test and post-test scores, were subjected to statistical analysis. The primary focus was to examine any significant differences in academic achievement among the three groups (classroom, classic laboratory, and augmented reality assisted laboratory) before and after the instructional interventions.
6	Qualitative Data Analysis	The qualitative data collected from in-class researcher observations and researcher interviews were analyzed thematically. Researchers identified recurring themes, patterns, and insights from the qualitative data to gain a deeper understanding of the pupils' experiences and perceptions in the different learning environments.

The combination of quantitative and qualitative data analysis allowed the researchers to provide a comprehensive assessment of the effects of different learning environments on pupil academic achievement and learning experiences. This mixed-methods approach provides a well-rounded perspective on the study’s research questions, offering insights into both quantitative outcomes and qualitative observations and interviews. The Shapiro-Wilk test is a statistical test used to assess whether a sample of data follows a normal distribution. In your study, the test was applied to the scores obtained by the two control groups and the experimental group on the Kazakhstani General National Test. The goal was to examine whether the scores within each group exhibited a normal distribution.

Table 14 – List of Shapiro-Wilk test phases

№	Phase	Explanation
1	Null Hypothesis	The null hypothesis in this test assumes that the data in the sample is normally distributed.
2	Alternative Hypothesis	The alternative hypothesis posits that the data in the sample does not follow a normal distribution.
3	Test Statistic	The Shapiro-Wilk test calculates a test statistic based on the data's order statistics (sorted values). This statistic is used to assess how closely the data follows a normal distribution.
4	P-Value	The test produces a p-value. If the p-value is less than the chosen significance level (alpha), typically 0.05, then the null hypothesis is rejected. A small p-value suggests that the data significantly deviates from a normal distribution.
5	Interpretation	If the p-value is less than 0.05 (or the chosen alpha level), you would reject the null hypothesis, indicating that the data does not follow a normal distribution. If the p-value is greater than 0.05, you would fail to reject the null hypothesis, suggesting that the data is normally distributed.

The Shapiro-Wilk test helps researchers assess whether assumptions of normality are met, which can be important for subsequent statistical analyses (Johnson, 1986:31). If the data is not normally distributed, alternative statistical methods or transformations may be needed. In your study, the test was used to check the normality of the Kazakhstani general national test scores for each group, which is a crucial step in assessing the appropriateness of parametric statistical tests like ANOVA (Analysis of Variance) that you might use to compare the means of multiple groups. If the data within any group did not pass the normality test, it might indicate the need for non-parametric tests or further data transformation (Sumadio, 2010:461). The Shapiro-Wilk test results indicate that the pre-test scores for all three groups (experimental group and two control groups) on the Kazakhstani General National Test follow a normal distribution. This is an important assumption when conducting certain parametric statistical tests. Since the p-values for the pre-test scores in all groups are higher than the accepted threshold of 0.05, it is reasonable to assume that the pre-test scores are normally distributed. Having normally distributed data allows for applying various statistical tests with confidence. In your analysis, you can proceed with the assumption of normality for the pre-test scores.

The results of the Shapiro-Wilk test indicate that the post-test scores for all three groups (experimental group and two control groups) on the Kazakhstani General National Test follow a normal distribution. Just like with the pre-test scores, this is an important assumption for conducting parametric statistical tests. Since the p-values for the post-test scores in all groups are higher than the accepted threshold of 0.05, you can reasonably assume that the post-test scores are normally distributed (Dünser, 2008:27). Having normally distributed data allows you to apply various statistical tests confidently in your analysis. You can proceed with the assumption of normality for the post-test scores. Performing parametric analyses is appropriate since you've established that your data is normally distributed. Here's a brief explanation of the statistical tests you mentioned This test is used to compare the means of two related groups to determine whether there is a statistically significant difference between them. In your case, you're comparing the pre-test and post-test scores within each group separately to see if there's a significant improvement after the intervention. Analysis of Variance is used to compare the means of three or more groups to determine if there are statistically significant differences between them. In your study, you are comparing the three groups (experimental and two control groups) to see if there are differences in their post-test scores after the intervention. By applying these tests, you can assess whether the augmented reality instructional material had a statistically significant impact on pupils' academic achievement compared to the control groups (Chen, 2018:295).

Results & Discussions

It is important to note that your initial analysis indicates that there were no significant differences in the pre-test scores between the experimental group and the two control groups. This suggests that, before the intervention (i.e., exposure to the augmented reality environment), the groups had similar levels of achievement. Next, we want to analyze the post-test scores to determine whether there were any significant differences in academic achievement after the intervention. You mentioned that ANOVA will be performed to compare the groups, which is a suitable statistical approach for this purpose (Freitas, 2008:30). Keep in mind that ANOVA will help you determine if there are significant differences in the post-test scores among the groups, and if any group performed significantly better or worse than the others after the augmented reality intervention. This analysis will provide valuable insights into the impact of the augmented reality environment on pupils' academic achievement. Your analysis shows that after the intervention, there were no significant differences in the post-test scores among the three groups, as indicated by the non-significant p-value ($p > .05$) from the ANOVA. This suggests that, on average, the academic achievement of all three groups was similar after they received their respective teaching methods.

However, it is worth noting that while there were no significant differences between the groups overall, you observed that the experimental group's score was higher than those of the other groups (Campos, 2011:33). This difference, while not statistically significant, might still be of practical importance and could suggest a positive trend in the augmented reality group's academic achievement. We can elaborate on these findings, highlighting that although there was no statistically significant difference, the experimental group seemed to perform slightly better in terms of academic achievement. Additionally, you can discuss the potential educational benefits and implications of using augmented reality in physics education, even if the differences are not statistically significant. Remember to interpret these findings in the context of your research questions and the broader implications for teaching and learning in physics using augmented reality. In your analysis, you performed t-tests to examine whether there were significant differences between the pre-test and post-test scores within each of the three study groups. Here is a summary of the results: For experimental Group the difference between the pre-test and post-test scores for the experimental group was found to be significant ($p < 0.05$), indicating that there was a significant improvement in academic achievement within this group after the augmented reality intervention. For First Control Group the difference between the pre-test and post-test scores for the first control group was not significant ($p > 0.05$), suggesting that there was no significant improvement in academic achievement within this group after the traditional teaching method in the classroom. For Control

Group the difference between the pre-test and post-test scores for the second control group was found to be significant ($p < 0.05$), indicating that there was a significant improvement in academic achievement within this group after the traditional teaching method in the classic laboratory environment.

These findings indicate that the experimental group, which received instruction through augmented reality, experienced a significant improvement in academic achievement, whereas the control groups, taught using traditional methods in either a classroom or classic laboratory, also demonstrated significant improvements. However, the effectiveness of the augmented reality intervention, as evidenced by the significant improvement in the experimental group, suggests a potential benefit of this approach for teaching physics. In your discussion, you can delve into the implications of these results, emphasizing the significant improvement in academic achievement in the experimental group compared to the control groups. You can also discuss the practical significance of these findings for educators and policymakers in the context of adopting augmented reality in physics education.

Additionally, consider the implications for future research and the potential for augmented reality to enhance learning outcomes in physics and other scientific subjects. To assess the impact of the instructional methods on the different levels of curriculum attainment, you can calculate and compare the mean scores of the three study groups on the post-test with respect to the four levels of curriculum attainment. This analysis will provide insights into how each instructional approach affected pupils across various levels of achievement.

Table 15 – General outline of how we approached this analysis

№	Phases of experiments	Actions to take in each phase
1	Define Curriculum Levels of Attainment	Clearly define the four levels of curriculum attainment based on the learning outcomes expected from the curriculum. You may need to specify the criteria for each level, such as what constitutes "low," "basic," "proficient," and "advanced" achievement.
2	Categorize Pupils	Categorize the pupils in each group into these four levels based on their post-test scores. For example, pupils with scores falling within a certain range could be classified as "low," "basic," "proficient «or» advanced" achievers.
3	Calculate Group Means	Calculate the mean post-test scores for each of the three study groups within each level of curriculum attainment. This will involve computing separate means for pupils classified as "low," "basic," "proficient," and "advanced" achievers in each group.
4	Compare Group Means	Compare the mean scores of the three groups within each level of curriculum attainment. You can use statistical tests (e.g., ANOVA) or visual representations (e.g., bar charts) to illustrate these comparisons.
5	Discuss Findings	Interpret the results of your analysis. Discuss whether there are significant differences in mean scores between the three groups at each level of curriculum attainment. Consider what these differences suggest about the effectiveness of each instructional method for pupils with different levels of prior knowledge and skill.
6	Implications	Discuss the educational implications of your findings. Consider how the instructional methods may cater to pupils at different levels of curriculum attainment and whether any particular method appears more effective for specific groups of pupils.
7	Limitations	Acknowledge any limitations of your analysis, such as sample size or potential confounding variables, and how these limitations may affect the generalizability of your findings.

By conducting this analysis, you can provide a nuanced understanding of how each instructional method impacts pupils across different levels of curriculum attainment, offering valuable insights for educators and curriculum developers. The results of your ANOVA analysis suggest that there were no significant differences between the groups' mean scores for the first attainment and the fourth attainment on the Kazakhstani general national test at the 0.05 level of significance (Matcha, 2011:189). This means that, for these two specific levels of curriculum attainment, the instructional methods used in your study did not produce significantly different effects on pupil achievement. However, it is essential to consider and discuss the implications of this finding. The lack of significant differences between the groups' mean scores for implies that, regardless of the instructional method used, pupils at the lowest curriculum attainment level did not experience significantly varied levels of improvement in their achievement on the Kazakhstani general national test. Similarly, for pupils at the highest curriculum attainment level, there were no significant differences in their achievement on the Kazakhstani general national test across the three instructional methods. This suggests that the more advanced pupils did not experience significantly different outcomes based on the instructional approach.

While these results indicate a lack of differentiation between instructional methods for pupils at these attainment levels, it is crucial to look into other levels where differences may exist. Analyzing and discussing the findings for these levels will provide a more comprehensive understanding of how the instructional methods impact pupils with different levels of prior knowledge and skill. Additionally, consider discussing potential reasons for the lack of significant differences. These reasons could be related to the nature of the curriculum content, the instructional methods employed, or the characteristics of the pupil sample. Addressing these factors can help interpret the results more effectively. The significant differences observed between the mean scores of the groups for the second and third attainments indicate that the instructional methods had varying effects on pupil achievement for these specific curriculum levels, which involve the right-hand rule. The General National Kazakhstani test revealed that the experimental group and both control groups had higher levels of achievement compared to the control group for the second attainment.

This suggests that the augmented reality instructional material, as well as the traditional classroom and classic laboratory environments, were more effective in improving pupil achievement compared to the control group that did not receive any of these instructional methods. The General National Kazakhstani test also showed that the experimental group achieved significantly higher levels compared to both control groups for the third attainment. This indicates that the augmented reality instructional material was particularly effective in enhancing pupil achievement, which involves the right-hand rule. These findings are essential as they highlight the specific areas of the curriculum where augmented reality instruction had a significant positive impact on pupil achievement. It is crucial to discuss the implications of these results, such as how augmented reality may be a particularly valuable tool for teaching topics related to the right-hand rule in physics.

Additionally, consider discussing potential reasons for these differences, such as the interactive and visual nature of augmented reality, which may have aided pupils' understanding of these complex concepts. In summary, your study's results suggest that while there were no significant differences for the first and fourth attainments, the augmented reality instructional material had a positive and significant impact on pupil achievement for the second and third attainments, particularly in understanding concepts related to the right-hand rule. These findings provide valuable insights into the effectiveness of augmented reality in teaching specific physics topics.

Table 16 – Results of t-test for pupils' pre-test and post-test scores on Kazakhstani general national test.

Group Type	Test Type	Number of pupils	X	SD	t	P
Experimental	Pre-test	260	70.50	11.489	3.986	0.001
	Post-test	260	60.24	13.458		
Control	Pre-test	260	64.48	11.694	1.473	0.154
	Post-test	260	58.20	10.501		
Traditional	Pre-test	260	67.00	8.879	4.422	0.000
	Post-test	260	61.58	10.730		

The findings of your study reveal important insights into the influence of different learning environments on pupil achievement in physics and the pupils' perceptions of their learning experiences.

Table 17 – Here are some key points to highlight based on your results

№	Key points	Explanations
1	Positive Influence of Learning Environments	The study demonstrates that the learning environments, including the augmented reality-assisted laboratory environment and the classic laboratory environment, had a positive influence on the academic achievement of pupils in both the experimental group and one of the control groups.
2	No Significant Influence on Control Study Group	Interestingly, the study found that the learning environment had no significant influence on the academic achievement of the pupils in the control study group, which was taught in a traditional classroom setting. This suggests that traditional classroom teaching methods may not be as effective in improving pupil achievement in physics as compared to more interactive environments.
3	Teacher's Role	Pupils' interviews revealed that the teacher's level of activity and teaching approach played a significant role in their learning experiences. In the traditional classroom environment, pupils reported that their learning was primarily determined by what the teacher explained. In contrast, pupils in the other learning environments, such as the augmented reality-assisted laboratory, felt more active in their learning process and attempted to learn physics independently through hands-on activities.
4	Pupil Engagement	The findings suggest that active engagement and experiential learning opportunities, such as those provided by augmented reality and laboratory environments, positively contribute to pupils' academic achievement in physics.
5	Autonomous Learning	Pupils' statements indicate that they were more motivated to engage in autonomous learning when exposed to more interactive and experiential learning environments. This aligns with the concept of constructivist learning, where pupils take an active role in constructing their knowledge.

Experimental study underscores the importance of considering the learning environment and teaching methods in the effective teaching of physics. Augmented reality and laboratory environments appear to offer benefits in terms of pupil engagement and achievement, particularly when compared to traditional classroom settings. These findings provide valuable insights for educators and curriculum designers seeking to enhance the teaching of complex subjects like physics. Conducted comprehensive observations during the study to capture various aspects of pupil feedback and teacher interactions. The data presented in Table 3 provide insights into these observations.

Table 18 – Observation of pupils

№	Observation	Explanation
1	Questioning	The frequency of questioning observed in the experimental group was notably higher compared to the two control groups. This suggests that pupils in the augmented reality-assisted laboratory environment were more actively engaged in asking questions, possibly reflecting a higher level of curiosity and interaction in this learning setting.
2	Replies and Confirmations	The experimental group also had higher frequencies of pupil replies and confirmations compared to the control groups. This implies that pupils in the augmented reality environment were more engaged in discussions and interactions related to the subject matter. This could be due to the interactive nature of augmented reality experiences.
3	Giving Examples	Interestingly, the control group taught in the classic laboratory environment had a higher frequency of giving examples compared to the other groups. This might indicate that pupils in this group were encouraged to provide real-world examples and practical applications during their lessons.
4	Overall Engagement	The mean scores for all observed aspects (asking questions, replying, giving examples, confirming) were generally higher for the experimental group compared to the control groups. This suggests a higher level of overall engagement and interaction among pupils in the augmented reality-assisted laboratory environment

The observations align with the findings related to pupil engagement and active learning in different learning environments. The augmented reality-assisted laboratory environment appears to foster more interactive behaviors, including asking questions, providing replies, giving examples, and confirming information among pupils. These observations support the idea that interactive and experiential learning environments can enhance pupil engagement and participation in the learning process.

Table 19 – Observation of learning environments.

№	Type	Experimental		Control		Control	
		f	Mean	f	Mean	f	Mean
1	Asking Questions	42	1.75	21	0.84	34	1.70
2	Replying	15	0.63	3	0.12	5	0.25
3	Confirming	45	1.87	32	1.28	35	1.75
4	Giving Examples	3	0.13	10	0.40	3	0.15
5	Giving Explanations	30	1.25	12	0.48	21	1.05

The data presented in Table 3, specifically regarding the mean number of questions asked by pupils during activities, provides valuable insights into pupil engagement and curiosity in different learning environments.

Table 20 – Here are some notable observations and implications:

№	Implications	Explanations
1	Question Types	The nature of the questions asked by pupils in the different groups is interesting. While the control groups asked questions related to clarifying their understanding of the right-hand rule, pupils in the experimental group did not raise questions about this topic. This could indicate that the augmented reality environment provided a clearer and more intuitive understanding of the right-hand rule, reducing the need for additional clarification.
2	Active Learning	Pupils in the experimental group were described as being more actively involved in the lessons and carefully observing the experiments conducted in augmented reality. This active participation aligns with the concept of experiential learning, where pupils are actively engaged in exploring and making sense of concepts through hands-on experiences.
3	Questioning Activity	The experimental group (augmented reality-assisted laboratory) had a significantly higher mean number of questions asked by pupils compared to the two control groups (classroom and classic laboratory). This suggests that pupils in the augmented reality environment were more actively engaged in questioning and seeking to understand the concepts being taught.

These observations support the idea that augmented reality environments can stimulate pupil curiosity and active participation in the learning process. Pupils in the augmented reality-assisted laboratory environment appeared to be more inquisitive and engaged in exploring the subject matter, potentially leading to a deeper and more meaningful understanding of the material. The observations and questions posed by the pupils in the control group, particularly in the classroom and classic laboratory environments, provide further insights into the challenges and limitations of traditional teaching methods for physics.

Table 21 – Traditional teaching methods for physics

№	Limitations	Explanations
1	Questions Reflecting Conceptual Difficulties	Pupils in the control group asked questions related to fundamental concepts in physics, such as the density of magnetic field lines at poles and the two-dimensionality or three-dimensionality of magnetic field line drawings. These questions suggest that they were grappling with abstract and theoretical aspects of the subject.
2	Theoretical Explanation	The control group received theoretical explanations about the direction of magnetic field lines, likely through verbal or written descriptions. However, the absence of visual aids or images made it challenging pupils to grasp these abstract concepts fully. This highlights the limitation of traditional teaching methods in conveying complex ideas.
3	Practical Challenges	The control group's experiences included practical challenges, such as insufficient force exerted by the magnetic field and difficulties in conducting experiments effectively. These challenges could have negatively impacted pupils' engagement and interest in the subject.

Overall, the observations and questions from the control group emphasize the need for innovative teaching approaches, such as augmented reality, to address the conceptual difficulties and limitations associated with traditional physics instruction. Augmented reality can provide visual and interactive experiences that enhance pupils' understanding and engagement with abstract concepts in physics.

Table 22 – The differences in the types of questions and engagement observed between the experimental group (the augmented reality group) and the control groups

№	Engagements	Explanations
1	In-Depth and Critical Questions	Pupils in the experimental group asked more advanced and critical questions about augmented reality and the instructional material itself. This indicates that they were not only engaged with the technology but were also curious about its inner workings and how it could enhance their learning experience. These questions reflect a higher level of inquiry and curiosity.
2	Teacher's Effort and Explanation	The teacher in the experimental group had to put in extra effort to address the pupils' advanced questions and provide satisfactory answers. This suggests that augmented reality stimulated more intellectual curiosity and required the teacher to adapt and respond to pupils' inquiries effectively.
3	Real-Life Associations	Another significant difference was observed in the pupils' ability to relate physics concepts to real-life situations. Pupils in the experimental group seemed to make more connections between magnetic fields and daily life, possibly because the augmented reality environment provided a more immersive and tangible experience.

These observations indicate that augmented reality not only engages pupils more actively but also encourages them to ask deeper and more meaningful questions, leading to a richer learning experience in the context of physics. Pupils' insights into the different learning environments provide valuable feedback on their preferences and perceptions. Pupils highlighted the augmented reality environment's ability to create a more realistic and immersive setting for activities. They appreciated how it enhanced visualization and concretized abstract concepts. This suggests that the technology's capacity to make learning more tangible and engaging was a significant factor in their positive perception. Pupils found the traditional classroom environment convenient due to the ready availability of textbooks and resources, which facilitated note-taking.

This environment seems to provide a structured and organized approach to learning. Pupils associated the classic laboratory environment with a positive attitude towards learning physics. They appreciated the hands-on experiments that allowed them to connect physics concepts with real-life scenarios. This suggests that practical experimentation is seen as an effective way to make physics more relatable and enjoyable. These insights underline the importance of catering to diverse learning preferences and the potential benefits of integrating technology like augmented reality to make learning more engaging and practical. It also emphasizes the role of real-world applications in enhancing pupils' understanding and interest in physics concepts. Pupils' insights on the effects of different learning environments on attention and curiosity provide valuable information. Pupils appreciated that the augmented reality environment employed new technologies, which automatically piqued their interest.

This suggests that the novelty and use of innovative technology can capture and maintain pupils' attention and curiosity, making the learning experience more engaging. Pupils did not view the traditional classroom as particularly conducive to capturing their attention and arousing interest in physics. Their perception of this environment's effectiveness seems to be influenced by the subject being taught, indicating that the classroom setting might need adjustments to make certain topics more engaging. Pupils found that the conduct of experiments in the classic laboratory environment attracted their attention and made physics a more interesting subject. This highlights the importance of hands-on activities and practical experiments in maintaining pupils' curiosity and engagement. These insights emphasize the role of technology in enhancing interest and attention, the need for tailoring classroom environments to the specific subject matter, and the effectiveness of practical experiments in making complex topics more engaging.

The pupils' insights on how different learning environments affect their emotions and thoughts during learning activities provide valuable information. Pupils expressed that this environment helped them overcome their fear of physics by introducing new technology and visualizing the subject matter. Their preference for this environment suggests that using innovative technology and visualization can make learning more appealing and less intimidating. This highlights the potential of augmented reality to positively impact pupils' emotions and thoughts, making them more receptive to challenging subjects. Pupils in the classroom environment felt that it could lead to a dislike for physics if it did not effectively facilitate understanding. This indicates that traditional classroom settings may need improvements in terms of engagement and effectiveness, especially for subjects like physics. In this environment, pupils might become less active and lose interest if the teaching methods do not align with their learning needs. Pupils found the classic laboratory environment appealing because it not only helped them cover the subject matter but also understand its practical applications. This suggests that hands-on experiences and real-world connections can enhance pupils' appreciation for a subject and make it more enjoyable. It also highlights the value of classic laboratory settings in teaching physics. These insights underscore the importance of technology and visualization in reducing apprehension about complex subjects like physics, the need for engaging and effective classroom environments, and the role of hands-on experiences in fostering interest and understanding.

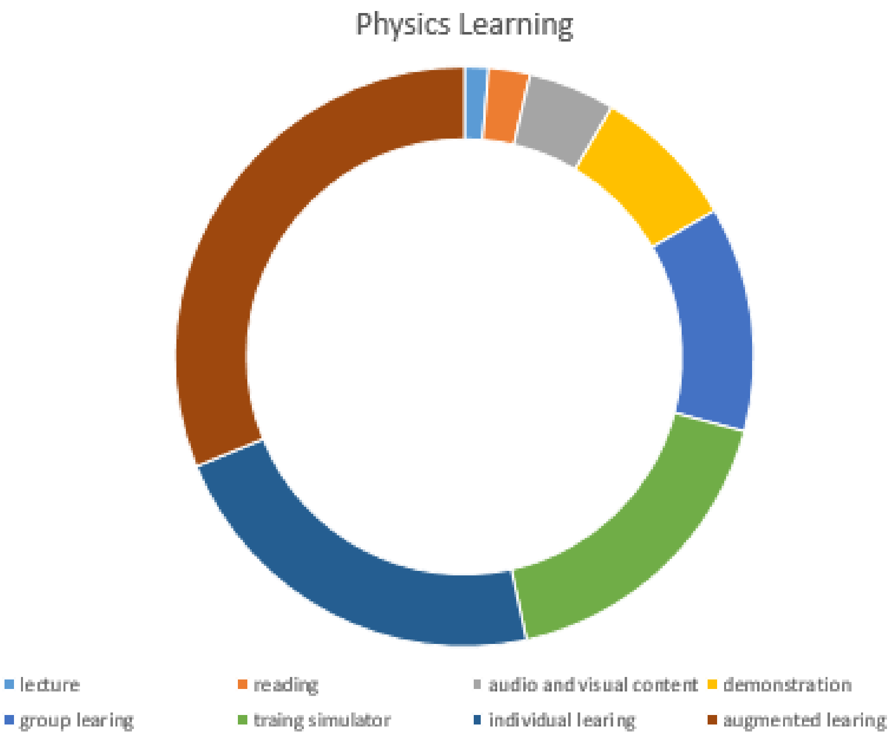

Figure 6 – The effectiveness of the main teaching methods

These insights underscore the advantages of combining traditional laboratory experiences with augmented reality to provide pupils with a comprehensive and productive learning experience that incorporates both hands-on experimentation and enhanced visualization.

Table 23 – Based on the feedback from the pupils, there were several insights regarding the shortcomings of the learning environments:

№	Learning environments	Role in experiment	Experience of pupils	Pupils' feedback
1	Augmented Reality Laboratory Environment	The pupils suggested that the augmented reality-assisted laboratory setup could be made more user-friendly and easier to set up and operate. They expressed a desire for more enriched visual elements or figures within the augmented reality environment. Some pupils anticipated that as technology continues to advance, the images and visuals in augmented reality could become even more realistic in the future.	In the augmented reality-assisted laboratory, pupils found it easier to perceive the magnetic field because the environment provided specific visualizations. This visual clarity facilitated communication with the surrounding context, making it easier for pupils to grasp the concept and relate it to real-life technologies.	Pupils in the augmented reality-assisted laboratory environment reported increased productivity. They viewed it as a valuable supplement to traditional laboratory activities. They noted that augmented reality could enhance the laboratory environment by adding visualizations, which further contributed to their learning experience.
2	Classroom Environment	The pupils found the traditional classroom environment to be less effective for their learning. They pointed out that the limited number of class hours allocated to physics made it challenging to incorporate extensive laboratory activities.	Pupils noted that in the traditional classroom environment, they struggled to directly and fully associate the subjects with everyday technologies. They felt that their ability to make these connections improved significantly only after receiving instructions and explanations from the teacher.	Pupils who received instruction primarily in the traditional classroom environment expressed dissatisfaction with the level of benefit it provided for understanding physics.
3	Classic Laboratory Environment	Pupils believed that the traditional laboratory setting could benefit from a less intensive curriculum, allowing for more time for experiments. They also noted that the number of laboratory activities remained limited due to the high volume of subjects in their curriculum.	In the traditional laboratory setting, pupils reported that conducting experiments made it easier to establish associations with real-world technologies. The hands-on experience of experiments prompted pupils to question how the principles they were learning might be applied in various technological contexts.	Those who had lessons in the classic laboratory environment found it beneficial, largely because of the hands-on experiments and practical activities that enhanced their understanding.

These insights from the pupils underscore the need for continuous improvement and adaptation in both augmented reality and traditional learning environments to better cater to pupils' needs and enhance their overall learning experience.

Discussion

As per the existing literature, augmented reality serves to solidify the information that pupils receive, fostering an environment conducive to learning. Particularly, when augmented reality experiments are simultaneous and interactive, pupils are empowered to ask more questions and engage in critical analysis. In our study, the instructional material leveraged augmented reality to concretize magnetic field lines and visually represent the strength and direction of a magnetic field. The pupils' positive feedback on this material corroborated this finding. Augmented reality was instrumental in enabling pupils to conduct critical analyses more effectively, ultimately leading to a better understanding of the right-hand rule of physics. These study results align with those of various other research studies in the literature, highlighting that augmented reality offers substantial benefits in scientific subjects that necessitate questioning and critical analysis. We stressed that pupils exhibit improved learning of concepts within an augmented reality environment, finding it easier to grasp information and perceive situations that may remain imperceptible even in real experiments. This observation helps account for the enhanced understanding of the right-hand rule of physics among the pupils in our study. The teacher responsible for implementing the augmented reality activities consistently reported that pupils who engaged with the augmented reality environment were better equipped to articulate distinctions between various scenarios during the activities, mainly owing to the visualization of magnetic fields using three-dimensional representations. Additionally, the teacher noted that pupils developed favorable behaviors and subsequently experienced an increase in their academic achievement. These findings underscore the significant positive impact of augmented reality on both comprehension and overall academic performance. It is important to emphasize that while augmented reality is a valuable tool for learning, it does not assure automatic academic success. Instead, it excels in facilitating learning by offering pupils alternative pathways to acquire knowledge. Research also suggests that pupils who engage with augmented reality enjoy the learning process and actively immerse themselves by applying critical thinking skills and taking on the role of a researcher. This supports the concept that an augmented reality-assisted environment presents diverse and alternative modes of learning. In our present study, pupils expressed a desire to integrate augmented reality as a supplementary component to the traditional laboratory setting for their physics lessons. They found augmented reality to be stimulating and captivating, further confirming the notion that augmented reality has the potential to invigorate and enrich the learning experience. Augmented reality serves as a valuable tool for supporting learning, aligning with findings from previous studies in the literature. Our research reinforced that augmented reality and virtual environments stimulate pupils' interest and boost their engagement. We also highlighted the positive impact of augmented reality visualizations on pupils' perception and comprehension. In our study, pupils using the augmented reality environment actively participated in their physics lessons, displaying a notable increase in their curiosity and willingness to ask questions. Augmented reality visuals played a pivotal role in enhancing their understanding, ultimately driving their motivation to learn. Collectively, these factors make the augmented reality environment a preferred choice for the teaching and learning process. The findings of this study align with those of previous research. It is evident that augmented reality fosters a highly interactive learning environment. Our observations support the idea that augmented reality not only enhances the ability of learning but also actively engages pupils, thereby increasing their willingness to participate. Furthermore, we anticipate that future school physics laboratories will be equipped with innovative technologies, including augmented reality, alongside portable devices, sensors, and advanced communication tools. In our study, we also noted that the augmented reality environment had a positive impact on pupils' inclination to ask questions, as well as fostering curiosity and interest. This effect was particularly pronounced due to the use of a magnetic field sensor in the instructional material, which provided a more authentic experimental setting, allowing pupils to solidify their understanding of concepts and explore real-life applications. The outcomes of this study make a noteworthy contribution to the limited but growing body of literature on augmented reality-enhanced learning in physics education. They also have implications for the evolution of augmented reality-equipped classrooms in the future.

Limitations

Acknowledging these limitations is essential for understanding the scope and potential implications of the study's findings, as it provides context for interpreting the results accurately.

Table 24 – List of limitations of study

№	Types of limitations	Explanations
1	Limited Generalizability	The findings may not be broadly applicable due to the use of convenience sampling, which could introduce bias in participant selection.
2	Short Duration	Extending the study duration to at least one academic year could have yielded more comprehensive and detailed results, providing a deeper understanding of the impact of augmented reality.
3	Content Enhancement	The GeoGebra content used in the study could be improved to cover a wider range of scientific problems, potentially making it more comprehensive and beneficial for pupils.
4	Instrument Validity	The validity of the responses collected from participants relies on their truthfulness and accuracy, which can be challenging to verify.

Conclusions

The impact of augmented reality on pupils' academic achievement reveals several key findings. Augmented reality learning environments prove to be effective for teaching high school physics concepts, particularly those related to physics. Facilitation of Learning: Augmented reality aids pupils in grasping complex aspects of physics, including understanding magnetic field dimensions, direction finding, and notably, the right-hand rule of physics. The integration of augmented reality into the learning environment has a positive impact on pupils' academic achievement, enhancing their understanding and performance in the subject matter. These findings collectively underscore the benefits of incorporating augmented reality into high school physics education, emphasizing its potential to improve learning outcomes and facilitate comprehension of challenging concepts in physics. The integration of augmented reality into the learning activities showed effectiveness of it. Pupils participated more in activities, felt more comfortable in the learning environment, answered questions related to the subject more comfortably and exhibited increased self-confidence. When physics was visualized using three-dimensional augmented reality displays and associated up-to date technologies, pupils found the topic of physics to be more interesting, which increased their buy-in to the lessons. Lessons were more effective in the laboratory-learning environment rather than an ordinary classroom, where images were supported with augmented reality, when pupils were taught how to apply physics to real-life situations, and when they were given examples from daily life. The feedback from pupils regarding the utilization of augmented reality in their learning highlights the several key points. When physics was taught in the laboratory, particularly in conjunction with augmented reality, it significantly enhanced the pupils' interest in physics experiments. It provided concrete examples of how the subject could be applied in real-life scenarios and created a visually immersive learning environment that focused on real-world contexts. The consensus is that augmented reality should not be viewed as a standalone learning environment for high school physics education. Instead, it is most effective when used as a supplementary tool to complement laboratory activities. These observations underscore the value of augmented reality in enriching the learning experience by making it more engaging and practical, while also emphasizing its role as a supportive component of physics education rather than a replacement for traditional hands-on laboratory work.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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