The Effect of Augmented Reality (AR) Supported Teaching Activities on Academic Success and Motivation to Learn Nuclear Physics among High School Pupils

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***Abstract*—The research aimed to investigate the impact of Augmented Reality (AR) supported teaching activities on pupils' academic success and motivation to learn physics, and their attitudes towards AR applications. The study focused on the "Nuclear Physics" unit in high school physics courses and employed the "Solomon Four Group Model" to control both internal and external validity. The study involved 120 pupils from two different schools, with two experimental and two control groups randomly assigned. First experimental group and first control groups completed pre-test and post-test assessments, while the second experimental group and second control groups only completed the post-test. Over a nine-week period, the experimental groups were taught using mobile AR applications, while the control groups followed the curriculum's planned activities. The data collection tools included the "Nuclear Physics Success Test" and the "Pupils' Motivation to Physics Learning" scale. Novelty of the research is about comparing and contrasting virtual laboratory learning environments with augmented reality learning environments. The research findings indicated that teaching with AR applications had a significant impact on pupils' academic success to learning physics. This suggests that teaching with AR applications is an effective educational approach to enhancing physics education among 11th-grade pupils. Despite the fact that virtual laboratories and augmented reality are both innovative technologies with the potential to enhance learning experiences, experimental research suggests augmented reality is more effective in developing pupils' critical thinking skills in high school physics lessons than virtual laboratories.**

***Keywords*—physics, augmented reality, cognitive learning, interactive teaching, interactive visualization, academic success, motivation to learn physics**

I. Introduction

Pupils prefer thinking about abstract processes in concrete terms. However, as their knowledge develops, they often hesitate to replace their existing models with more scientifically accurate ones. The concept of atomic structure pose challenges for many pupils, and there are two identified classes of scientifically incorrect misconceptions among them. First, some pupils lack a sufficient understanding of particle-related ideas, leading to confusion in labeling diagrams as they struggle to differentiate between various concepts. Second, other pupils may grasp the particle concept but face difficulties understanding particle interactions, exemplified by misconceptions such as thinking that neutrons in the nucleus neutralize the charge of protons. Pupils rarely connect electrostatic principles learned in physics to the domain of chemistry. For instance, some pupils may believe in the indivisibility of atoms when studying chemistry, despite accepting the concept of radioactive decay in physics. Another prevalent misconception is the belief that electrons pushing upon it, implying an incorrect understanding that electrons and protons would repel each other, hold the nucleus together. The notion of the atom being indivisible is widespread among pupils, occurring not only among those with insufficient knowledge of atomic structure but also among those familiar with subatomic particles. There is a common conception that electrons strictly belong to a specific atom, leading to potential misconceptions regarding molecular bonding. Overall, learning about atomic structure proves to be a challenging task for many pupils.

Augmented Reality (AR) technology into the field of education has introduced exciting opportunities to enhance the learning experience [1]. By merging virtual elements with the real world, AR applications provide pupils with interactive and immersive educational content. In domains like engineering and architecture education, where understanding three-dimensional objects and spaces is critical, AR technology has proven to be invaluable [2]. It empowers pupils to visualize intricate concepts, animate objects, and explore complex designs, ultimately leading to a deeper comprehension of the subject [3]. As technology continues to advance, students poise AR applications to play an increasingly significant role in shaping the future of education across various disciplines.

Using Augmented Reality applications to improve physics education represents a significant advancement in the teaching of physics [4]. Visualizing physics objects and concepts in three dimensions can pose a considerable challenge for pupils. Augmented Reality can have a substantial impact on physics education in multiple ways.

We recognize the potential benefits of Augmented Reality (AR) technology in addressing challenges in scientific education, particularly in learning physics. We express a strong belief in the necessity of incorporating augmented reality technology into the learning environment for physics. We ground this belief in our perception of the challenges faced by science education. We align the adoption of augmented reality with global trends that emphasize enabling pupils to manage their learning based on their preferences, interests, and abilities. This suggests a recognition of the importance of personalized learning approaches. The prevalence of smart devices among general education pupils with the researchers highlighting their use for communication, gaming, and social networking. This observation serves as a rationale for integrating augmented reality into the learning process, capitalizing on the widespread availability of technology. We identify deficiencies in traditional teaching methods, specifically in presenting curricula and enriching them with practical experiments, videos, and visual aids. They link these shortcomings to a failure in pupils' understanding of scientific concepts and a resulting lack of motivation to learn. The researchers conducted an exploratory study, a scarcity of specialized studies on the effects of augmented reality technology in improving acceptance and learning outcomes. This research gap serves as a motivation for the current study. The researcher specifies a focus on academic success in the context of teaching nuclear physics using augmented reality. This suggests a targeted investigation into the impact of AR on understanding and performance in a specific area of physics. Our rationale for the study in a perceived need for innovative solutions to enhance science education, with augmented reality technology being seen as a promising tool to address deficiencies in traditional teaching methods and improve pupils' acceptance and academic success in physics, particularly in nuclear physics.

The research questions address the key objectives of this study, which aims to investigate the impact of teaching with AR-enhanced materials on pupils' academic success and motivation within the context of the "Nuclear Physics" unit in the Physics course as shown in Table 1. Table 2. demonstrates the comparison of AR with VR and virtual laboratories in educational purposes.

By addressing these research questions, this study aims to provide valuable insights into the effectiveness of AR-enhanced teaching in the "Nuclear Physics" unit. The results will contribute to the growing body of knowledge on the use of technology-enhanced teaching methods and their impact on pupils' learning outcomes and motivation. It is important to note that the impact of teaching methods and the correlation between motivation and academic success can vary among individuals. Factors such as the quality of instructional design, teacher-pupil interactions, and the overall learning environment play a significant role in shaping these outcomes. Research studies specific to the context and population of interest would provide more nuanced insights into these relationships.

The research objectives outlined in this research are clear and specific.

1) Detecting the level of achieving augmented reality technology in teaching a nuclear physics. The primary goal is to assess or determine the level of effectiveness or success in using augmented reality technology for teaching a specific unit related to medical technology. This aim suggests an evaluation of how well augmented reality technology performs in delivering content related to medical technology. The assessment could involve various criteria, such as comprehension, engagement, and overall learning outcomes.
2) Identifying the significance of differences in pupil scores in the scale of acceptance before and after the application of mobile augmented reality technology. The aim is to measure and understand the extent of changes in pupil attitudes and acceptance towards using augmented reality technology by comparing their scores before and after the application of this technology. This aim implies an investigation into the impact of augmented reality on pupils' acceptance. Analyzing the differences in scores before and after the application can provide insights into the effectiveness of the technology in influencing pupils' perceptions.

Table 1. The research questions and the significance of each question

#	Research question	Importance of question
1	Does the experimental procedure lead to a significant difference between academic success and motivation pre-test and post-test scores of the groups stimulated by the pre-test in the physics course?	This question examines whether the AR-enhanced teaching procedure results in a significant change in academic success and motivation from the pre-test to the post-test within the groups that initially underwent the pre-test. It will help identify the impact of the teaching method on pupil performance and motivation over time.
2	What is the impact of AR-enhanced teaching method on pupils' academic success in physics?	AR can enhance engagement by providing interactive and visually stimulating content. Increased engagement often correlates with improved academic success. The interactive and 3D visualization features of AR may contribute to better conceptual understanding, helping pupils grasp complex physics concepts more effectively. AR's immersive nature may aid in information retention, and the application of knowledge in real-world scenarios through AR simulations can potentially improve academic success.
3	What is the impact of AR-enhanced teaching method on pupils' motivation to learn physics?	AR can make physics lessons more interesting by offering interactive and visually appealing content, potentially increasing pupils' interest in the subject. The hands-on and experiential nature of AR may enhance intrinsic motivation by providing pupils with a sense of autonomy and control over their learning experiences. AR applications that connect physics concepts to real-world applications can make the subject more relevant to pupils, fostering motivation to explore and understand the content.
4	What is the nature of the correlation between motivation to learn nuclear physics and academic success?	Higher motivation to learn nuclear physics may be positively correlated with academic success. Motivated pupils are likely to invest more time and effort in understanding and mastering the subject matter. Motivated pupils may exhibit better study habits, such as regular attendance, active participation, and a willingness to seek additional resources. These habits can contribute to academic success. Pupils with high motivation may also have a higher level of self-efficacy, believing in their ability to succeed in learning nuclear physics. This confidence can positively influence academic performance.
5	When pre-test is controlled, does the experimental procedure make a significant difference between the academic success and motivation post-test scores of the pupils in the pre-test groups?	This question controls for the influence of the pre-test and specifically focuses on whether the AR-enhanced procedure leads to significant differences in academic success and motivation between pupils who took the pre-test. It helps to isolate the effect of the AR-enhanced teaching method.

This work is a valuable contribution to the academic community, and it is great to see the effort we are putting into filling gaps and driving innovation in this area.

We have presented the hypotheses we have presented articulate the expected outcomes related to the research questions:

H1: Augmented reality technology does not achieve an acceptance rate of over 90% among pupils for teaching the nuclear physics unit. The hypothesis suggests a skepticism or expectation that the acceptance level of augmented reality technology for teaching nuclear physics will not exceed 90%. If the research finds that acceptance surpass this threshold, it would contradict the hypothesis.

H2: There are no statistically significant differences (at $\alpha \leq 0.05$) between pupil scores in the acceptance of the augmented reality technology scale before and after the application. This hypothesis posits that the application of augmented reality technology will not lead to statistically significant changes in pupils' acceptance scores. If the research shows a statistically significant difference, it would suggest that the application of augmented reality has had a measurable impact on pupils' acceptance.

Table 2. Comparison of AR with VR and virtual laboratories in educational purposes

Comparison factors	Virtual Reality (VR)	Virtual Laboratory:	Augmented Reality (AR)
Definition	VR immerses users in a completely virtual environment, isolating them from the physical world.	Virtual laboratories replicate physical laboratories in a digital space, allowing students to conduct experiments in a simulated environment.	AR overlays digital content onto the real-world environment, enhancing the physical world with computer-generated information. AR blends virtual and real-world elements.
Educational Applications	VR provides realistic simulations, allowing students to explore environments or scenarios that may be impractical or unsafe in reality.	Virtual labs offer a safe and cost-effective way for students to conduct experiments that may be difficult or dangerous in a physical setting.	AR allows for interactive experiences, enabling students to engage with content and manipulate virtual objects in a real-world context.

II. Literature Review

A. Augmented Reality Technology

AR enables pupils to comprehend complex physical concepts that can be elusive through traditional teaching methods. For example, it can breathe life into abstract scientific models and experiments, rendering them more comprehensible [5]. AR applications empower pupils to interact with virtual objects and simulations, fostering a hands-on learning experience. This interactivity can enhance their grasp of physics principles. AR can simulate real-world physics phenomena, making it easier for pupils to apply theoretical knowledge to practical situations [6]. For instance, it can replicate physics experiments with no physical equipment. One of the most noteworthy benefits of AR in physics education is its capacity to make learning more engaging and enjoyable [7]. Pupils are often more motivated to explore and experiment with AR-based lessons, which can lead to improved retention of information. We can customize AR to align with pupils' individual learning styles and paces, offering adaptive learning experiences that cater to each pupil's needs. AR applications can provide real-time feedback on physics problems and experiments, assisting pupils in identifying and learning from their mistakes instantly [8]. Furthermore, AR technology offers the flexibility of accessing physics laboratory simulations and experiments from virtually anywhere, diminishing the requirement for costly laboratory equipment and the necessity of physical presence in a classroom. AR can also facilitate interdisciplinary learning, enabling pupils to explore the connections between physics and other subjects. Immersive AR experiences are more likely to be kept in pupils' long-term memory, enhancing their grasp of physics concepts. In addition, AR has the potential to make physics education more inclusive by accommodating different learning styles and abilities [9]. Augmented Reality stands as a transformative force in physics education, offering a dynamic and effective approach for teaching complex concepts [10]. Traditional teaching methods often struggle with conveying intricate and abstract ideas, especially in fields like physics. Augmented Reality applications present an exciting alternative by seamlessly blending the real world with virtual elements. This fusion enables pupils to interact with mathematical concepts in a tangible, three-dimensional manner, significantly deepening their understanding. In disciplines such as physics, where spatial visualization and mathematical acumen are paramount, AR emerges as a potent educational tool. It provides an immersive learning experience, enabling pupils to grasp intricate physical shapes and principles more easily [11]. By overlaying virtual objects on the real environment, AR applications bridge the gap between theory and practice, allowing pupils to gain a profound comprehension of these theoretical concepts. Integrating of AR into physics education has the potential to enhance pupils' cognitive skills, making them more adept at solving physics problems and conceptualizing abstract ideas. This innovative approach aligns seamlessly with the evolving landscape of modern education and presents a valuable addition to teaching methodologies across diverse disciplines [12].

B. Experiential Learning in Augmented Reality

Studies investigating the use of AR applications like PhysicsAR to enhance spatial visualization skills and academic success among sixth-grade pupils in a physics course have shown promising results [13]. Using three-dimensional shapes of rigid bodies through AR applications has not only made learning more engaging and enjoyable for pupils, but has also contributed significantly to their academic success. The interactive and fun learning experience offered by AR applications can transform education, making it more accessible and enjoyable for pupils. Research exploring the integration of AR-enriched learning materials to enhance the success and satisfaction levels of third-grade computer physics pupils is a valuable contribution to the educational realm [14]. Functional applications like NucPhysAR have provided pupils with interactive and engaging avenues to learn physics concepts. The positive impact on pupil success and satisfaction underscores the potential benefits of incorporating augmented reality into the classroom environment. Studies observing atoms and molecules in three dimensions through AR technology have yielded promising outcomes, with pupils expressing a desire to continue using this technology for learning [15]. The ability to observe complex scientific concepts like atom structures in three dimensions enhances pupils' spatial abilities and overall success, showcasing the supportive role AR can play in teaching intricate scientific principles [16].

C. The Importance of Augmented Reality in Education

The integrating AR applications to education, especially through mobile devices, has opened up new possibilities for enhancing teaching and learning in every field of physics [17]. These AR applications can serve as valuable educational tools to make abstract and complex concepts more accessible and engaging for pupils. The ability to visualize and interact with virtual objects related to space and the universe can provide pupils with a more immersive and effective learning experience. It is exciting to see how technology is transforming the way we teach and learn, making educational content more interactive and accessible [18]. Traditional classroom settings often face limitations in teaching complex physics concepts, such as the nuclear system and atom systems. AR applications offer an effective solution by bringing this abstract and distant phenomenon to life in an interactive and engaging way. By using AR, pupils can explore the atom system and electrons as if they were right there, providing a much deeper understanding of these nuclear bodies [19]. The ability to visualize and interact with atom structure concepts through AR applications can significantly enhance the learning experience in physics. It is exciting to witness how technology is revolutionizing education and making once-difficult subjects more accessible to pupils. Research work in designing supporting materials and developing AR activities for the "Nuclear Physics" unit, in consultation with educational design experts, is commendable [20]. This innovative approach aims to enhance the success levels and attitudes of high school pupils by supplementing traditional physics instruction with AR-enhanced teaching materials. By providing pupils with the opportunity to explore complex topics in physics through AR, we are helping them discover and learn about the universe in a more realistic and engaging manner. Using AR applications in education has the potential to revolutionize the way pupils engage with and understand complex subjects [21]. This research is contributing to a growing body of evidence that supports the effectiveness of AR in enhancing the learning experience. Research efforts to make learning more engaging and effective are truly valuable. The results of the semi-experimental study clearly show the positive impact of AR technology on both pupils' success levels and their attitudes toward the physics course [22]. The pupils who experienced a learning environment supported by AR technology as shown in Fig. 1, had better outcomes compared to those taught using traditional methods.

Fig. 1. Augmented reality headsets for physics laboratory experiments.

This suggests that integrating AR applications into the educational process can significantly enhance the overall learning experience and improve pupil performance [23]. The availability of applications like PhysicsAR, GeoGebra, and PhysLabAR is a promising sign of the growing interest in AR technology within the education sector, as shown in Fig. 2. These tools might transform the way physics is taught and learned, making it more interactive and enjoyable for pupils [24].

Fig. 2. Applying augmented reality headset for nuclear physics module experiment.

This research provides valuable insights into the effectiveness of AR in enhancing physics education, and it contributes to the broader conversation about the role of technology in improving pupil outcomes [25]. The premise of the research, which focuses on high school pupils and their ability to learn more effectively through visual and tangible experiences, aligns with established educational principles as shown in Fig. 2. Pupils of high school age often benefit from hands-on learning experiences, and the ability to visualize and interact with objects like the atom system, electrons, and microscopes can significantly enhance their understanding of complex topics within the "Nuclear Physics" learning domain. Augmented reality technology offers a promising solution for providing three-dimensional visualizations of these concepts and creating interactive and immersive learning environments [26]. This approach opens up exciting possibilities for teaching subjects related to the world and the universe, making learning more engaging and effective. This research is particularly valuable because AR technology is still in its early stages of adoption in educational settings, and there are a few reports assessing its use in physics education [27]. By exploring this technology in high school education, we are contributing to the growing body of knowledge in education technology [28]. Research work in this area has the potential to make a significant impact on how pupils learn and engage with complex subjects like physics, as shown in Fig. 3.

Fig. 3. The experimental design: Augmented reality headset for physics laboratory experiments.

III. Research Methodology

A. Research Model

Fig. 4. shows that experimental designs play a crucial role in strengthening scientific validity by systematically exploring cause-and-effect relationships between variables.

Fig. 4. Process of experiments in physics module.

We break down the significance of ensuring both internal and external validity in educational research. Internal validity is essential to establish whether the independent variable (in this case, the use of AR-enhanced teaching) causes any observed changes in the dependent variable (academic success and motivation). It involves controlling potential confounding factors and ensuring that the manipulation or treatment (AR-enhanced teaching) handles the outcomes. By using experimental designs, researchers can implement rigorous controls to minimize internal validity threats, such as selection bias, history, and maturation. External validity is equally important as it addresses the generalizability of the research findings. It determines whether the results observed in the study can be extended to a broader population. In educational research, this means assessing whether the effects of AR-enhanced teaching on academic success and motivation can apply to pupils in different settings or contexts. Using experimental designs allows researchers to replicate the study in various educational settings, which can enhance the external validity of their findings.

B. Experiential Processing Materials

The researchers carefully structured the experimental process through the preparation of lesson plans and activities. We designed these instructional materials to align with the AR applications and to meet the objectives of the Physics Education Program. For the control groups, we developed lesson plans under the activities specified in the standard physics curriculum. To ensure balance between the research groups, the researchers delivered lessons in both the experimental and the control groups. Since the pupils had not previously encountered AR applications and required technological skills, it was essential to provide them with prior information and orientation. The research spanned six weeks, encompassing four weeks of experimental application, one week of pre-testing, and one week of post-testing.

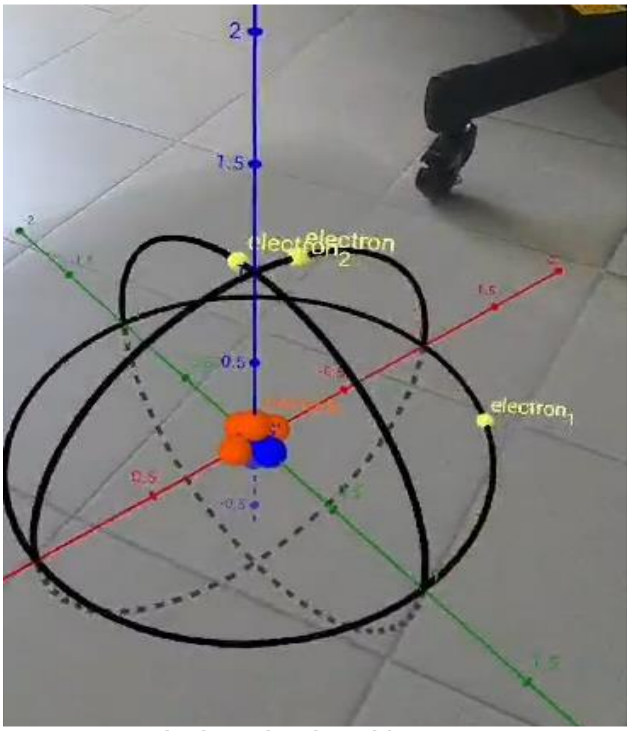

Fig. 5. Augmented reality nuclear physics laboratory experiment scene.

During this period, researchers conducted activities involving AR applications in the experimental groups, while the control groups engaged in activities outlined in the standard curriculum. The researchers employed AR applications to teach various physics topics in experimental groups (Fig. 5). In the "Electrons and Atom Movement" subject, pupils could visualize and observe electrons, atoms, protons, and neutrons in three-dimensional representations. This application also enabled pupils to understand that the atom and electrons. Similarly, in the "Atom Structure" subject, AR applications were used in the experimental groups to depict the movement of electrons around the atom. Instead of learning about the features of electrons from two-dimensional illustrations in books, pupils gained a comprehensive understanding of various electron characteristics, such as their proximity to the atom, number of electrons, size, rotation speeds. Additionally, pupils who studied the rotations of the atom, and the electron through AR applications had a better grasp of quantum-related concepts (Fig. 6). In the "Research" subject, AR applications were employed to help pupils observe the structure of electrons in three dimensions using virtual reality. Fig. 6 shows that throughout the experimental process, pupils expressed they had never seen an atom structure so realistically before.

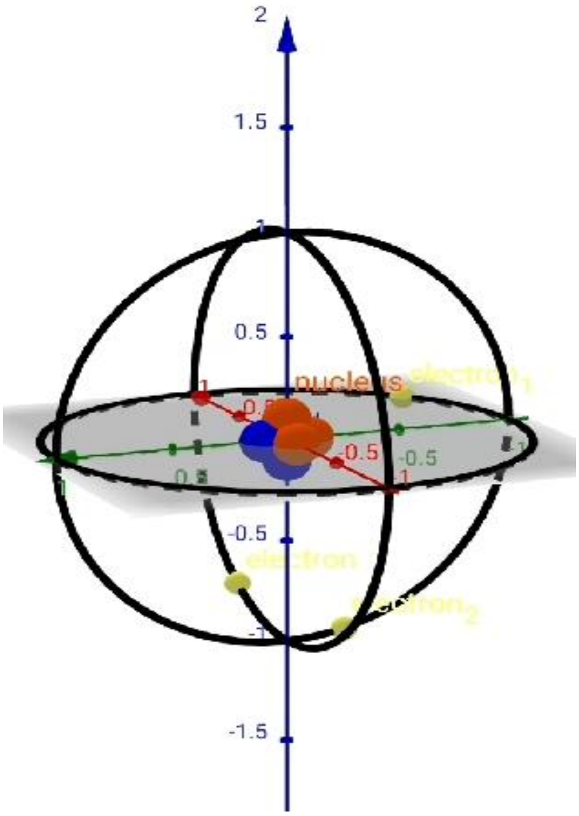

Fig. 6. Nuclear physics virtual lab.

C. Solomon Four-Group Experimental Model

This choice of the Solomon four-group experimental model, which includes both pre-test and post-test groups and control groups, is valuable in this context. It helps protect internal validity by allowing us to assess the impact of AR-enhanced teaching while controlling for pre-existing differences and threats to validity. By conducting this research in different schools, we are increasing the external validity of these findings. This approach to using experimental designs and addressing internal and external validity concerns shows a comprehensive and rigorous research method. The “Solomon Four-Group Experimental Design” is a research design often used in experimental studies to investigate the effects of an intervention, treatment, or independent variable on a particular outcome or dependent variable. This design is especially useful when researchers want to assess both the immediate and longer-term effects of an intervention while addressing potential threats to internal validity. The design is named after its developer, Donald Campbell, and is considered a powerful method to ensure both internal and external validity in a study. In this design, we have two groups, such as one Experimental (E) group and one Control (C) group. Each of these groups is further divided into two subgroups: one that receives a pre-test (O1) before the intervention and one that does not receive the pre-test. So, we have four groups in total: Experimental Pre-test (EP), Experimental No Pre-test (EN), Control Pre-test (CP), and Control No Pre-test (CN). The experimental group (both EP and EN) receives the treatment or intervention (in this case, AR-enhanced teaching), which is the independent variable. Both the pre-test and post-test measurements are taken for all four groups. The pre-test measures the baseline of the dependent variable (academic success and motivation), and the post-test measures the outcomes after the intervention. Researchers can compare the data across all four groups to draw several conclusions. The EP group’s post-test scores show the immediate effect of the intervention. The difference between the EP and EN post-test scores helps understand the long-term effects of the intervention, as the EP group received both pre-test and intervention. Comparing the CP and CN groups helps assess the effect of the pre-test alone. By comparing the differences between the EP and CP groups and the EN and CN groups, researchers can gauge the impact of the intervention compared to no intervention. The “Solomon Four-Group Experimental Design” is valuable because it addresses potential threats to internal validity by comparing groups with and without pre-tests. It also allows researchers to examine both the short-term and long-term effects of an intervention. It enhances external validity by providing a comprehensive view of the intervention’s impact across different contexts. This design is useful in educational research, where assessing the effectiveness of teaching methods, curricula, or interventions is common. This helps ensure robust research findings and their applicability in broader educational settings. Using of the “Solomon Four-Group Experimental Design” in this research is an excellent choice, as it provides a robust framework for investigating the impact of an intervention while addressing both internal and external validity. We have design how this design was implemented in this study. This research involved four groups, each with a specific purpose. experimental pre-test group received both the pre-test and the intervention (AR-enhanced teaching). The experimental pre-test group did not receive the pre-test but did receive the intervention. This group received the pre-test but did not receive the intervention. Control No Pre-test group neither received the pre-test nor the intervention. The inclusion of pre-test in the EP and CP groups allowed we to assess whether there was pre-test sensitivity. It helped determine whether the pre-test itself had any impact on the results or if the observed changes were because of the intervention. By comparing the EP and EN groups, we assessed the immediate effects of the intervention. We are comparing the EP and CP groups and the EN and CN groups allowed us to investigate the long-term effects of the intervention, as well as the effects of the pre-test. The “Solomon Four-Group Experimental Design” is highly regarded for its ability to ensure both internal and external validity. We maintained internal validity by distinguishing between the effects of the pre-test and the intervention on the outcomes, while external validity is enhanced by demonstrating the generalizability of the results to a broader population. This research design is particularly valuable in educational contexts, as it provides a comprehensive assessment of the effectiveness or interventions while considering various factors that might affect the results. Fig. 7 shows that the Solomon four-group experimental model is especially useful in addressing concerns related to pre-test sensitivity and is a powerful tool for educational researchers seeking robust and reliable findings.

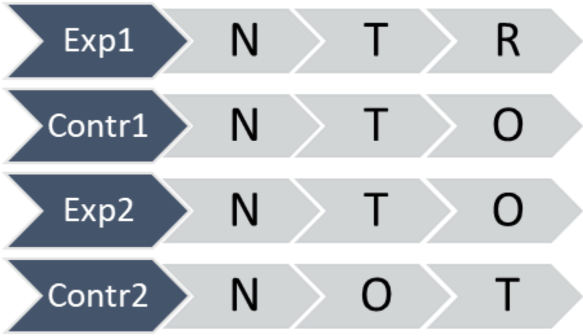

Fig. 7. The structure of experimental design.

The study employed the 'Solomon Four-Group Experimental Design,' a robust research model known for its simultaneous reinforcement of both internal and external validity. Using of the Solomon four-group experimental model in this research is a noteworthy and innovative approach. This model, which ensures the validity of experimental research, is relatively more common in educational studies, particularly those involving emerging technologies like Augmented Reality [29]. By employing this model, this research contributes to the field by demonstrating a method that safeguards both internal and external validity [30]. Fig. 5 shows that the research's originality is also clear in AR applications. As AR technology is still in its early stages in the educational field, conducting a fully experimental study based on the Solomon four-group experimental model is a pioneering effort [31].

D. Experimental Treatment

We have determined a research design that aligns with our research objectives. We defined control and experimental groups. We planned for data analysis methods that will interpret the results. We implemented mechanisms for collecting feedback from participants during the study. This can include surveys and interviews to gather qualitative insights. We developed a realistic timeline for the pre-application phase, including the preparation, training, and pilot testing stages. By addressing considerations in the pre-application phase, we lay the groundwork for the research study on the application of augmented reality tools in education. This careful preparation enhanced the validity of the study and contributes to the meaningful integration of AR into the educational environment. Establishing a control class and experimental class in learning nuclear physics with augmented reality involves thoughtful planning and consideration. We clearly outline the educational goals and objectives of the nuclear physics curriculum. Identify specific learning outcomes that augmented reality is expected to enhance. We developed research questions that address the impact of augmented reality on nuclear physics learning. We consider aspects such as comprehension, engagement, and retention. We defined criteria for selecting pupils for the control and experimental groups. We consider factors like prior knowledge of nuclear physics, academic performance, and any other relevant demographic variables. We decided whether we will assign pupils to the control or experimental group randomly or if efforts will be made to match the groups based on specific characteristics. Randomization helps control potential biases. We conduct a baseline assessment to understand the initial knowledge and skills of pupils in both groups. This can include pre-tests or surveys related to nuclear physics concepts. We developed a detailed plan for implementing augmented reality in the experimental class. We specified the AR tools, applications, or experiences that pupils in the experimental group will receive, and contrast this with the traditional methods used in the control class. We considered the well-being of the pupils and ensure that they have an opportunity to benefit from the educational interventions being implemented. We developed a comprehensive plan for collecting data from both the control and experimental groups. This may involve post-tests, surveys, observations, or other assessment methods to measure the impact of augmented reality on learning outcomes. We planned for statistical analysis to compare the performance of the control and experimental groups. We used appropriate statistical tests to determine if any observed differences are statistically significant. We implemented mechanisms for collecting feedback from both pupils and instructors throughout the study (Fig. 8). Our approach ensures that the study is well designed, ethical, and capable of providing meaningful insights into the effectiveness of AR in nuclear physics education.

Fig. 8. Pupils are taking post-test about nuclear physics module.

E. Research Work

Research work serves as an example of how to evaluate the effectiveness of AR-enhanced teaching methods while addressing potential threats to research validity. This combination of novel method and the application of AR technology to high school education underscores the importance and uniqueness of this research. It has the potential to guide future studies in education technology and inspire others to explore similar research methodologies [32]. This design facilitated an examination of pre-test sensitivity, enhancing external validity alongside internal validity. To illustrate this model, we provided a symbolic representation in Table 3. As depicted in Table 3, the research encompassed two experimental and two control groups. One set of groups underwent pre-test assessments, while the other set did not receive pre-tests. This approach allowed for an evaluation of the independent variable's impact on the outcomes by comparing the results of pre-test and post-test applications within the first experimental and control groups. Meanwhile, it also explored whether the pre-test itself influenced the results by omitting the pre-test in the second set of experimental and control groups.

Table 3. A figurative illustration of the Solomon four-group experimental model

Sets	Neutrality	Pre-Test	Conduct	Post-Test
Experimental (1)	N	yes	T	yes
Control (1)	N	yes	T	yes
Experimental (2)	N	yes	-	yes
Control (2)	N	yes	-	yes

In experimental research designs, it is common to use multiple groups, typically including experimental and control groups, as shown in Table 3. The composition of these groups should be based on an unbiased assignment. Hence, in this study, we created research groups through random assignment to ensure that any observed differences in results between the experimental and control groups remain unbiased. We conducted these procedures following the framework of the Solomon four-group experimental model, as illustrated in Table 3. As illustrated in Fig. 5 the experimental groups received instruction with the help of AR applications aligned with the daily lesson plans prepared by the researchers, while the control groups received instruction solely under the daily plans. Prior to the commencement of the study, the 'Nuclear Physics Success Test' and 'Pupils' Motivation to Physics Learning' scales were administered as pre-tests to Experimental (1) and Control (1) groups. Subsequently, post-tests were administered to all groups at the conclusion of the research. In the process of selecting the groups, a one-way Analysis of Variance (ANOVA) was conducted to assess whether there existed a significant difference in the year-end physics lecture averages among all eleventh-grade pupils in these two schools as presented in Table 4.

Table 4. Results of one-way ANOVA for the physics laboratory averages of the eleventh grade pupils in class A and B during the academic year of 2023

Alteration	Sum of Square	df	Mean of Square	F	*p*
Among Groups	2020.05	7	515.51	1.71	0.11*
Inside Groups	71052.07	351	261.33	1.12	0.09
Total	91073.12	358			

*$p < 0.05$

Table 5 reveals that there was no noteworthy distinction in the average grade for physics lectures during the 2023 academic year among all eleventh-grade groups in the two schools. Given the lack of statistically significant differences between the groups, four groups were randomly chosen to participate in the study. Subsequently, the research was conducted with a total of 120 pupils, who were allocated into experimental and control groups, as depicted in Table 5.

Table 5. Demographic individualities of pupils in among research participants

Class	Groups	Number of participants		
		Male	Female	Total
Class A	Control (1)	15	15	30
	Control (2)	13	17	30
Class B	Experimental (1)	16	14	30
	Experimental (2)	15	15	30

Due to the extensive duration of the research, the researcher's logistical constraints, and the need for technical resources, a convenient sampling method was employed to select the schools involved in the study. Two different schools were chosen for the research to prevent any potential impact of the experimental procedures on the control group. Consequently, great care was taken to select the experimental groups from the same school. Moreover, in classrooms not involved in the research but situated in the same school where the experimental procedures were carried out, lessons were also conducted with the assistance of AR applications. Fig. 9 illustrates this strategy designed to avoid any sense of exclusion and guarantee that all students can derive advantages from comparable activities. The researcher personally conducted the activities in all the classrooms within the school where the research was conducted.

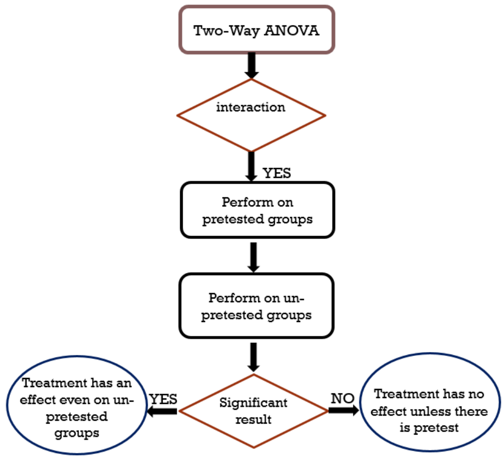

Fig. 9. Procedures followed during experimental process.

This experience led to increased interest and aspirations to become scientist. At the conclusion of the four-week experimental period, both the "Nuclear Physics Success Test (NPST)" and the "Pupils' Motivation to Physics Learning (PMPL)" scales were administered to all groups as post-tests.

F. Population and Sample

Prior to beginning the experimental phase, we chose the groups participating in the study from two state schools in the Ili district during the second semester of the 2022–2023 academic year. The study involved 120 students in the 11th grade, ranging in age from 15 to 17 years. We employed pretest-posttest questionnaires and observation instruments to collect data on the students' learning experiences in physics.

G. Nuclear Physics Success Test

The "Nuclear Physics Success Test (NPST)" comprises 35 questions and was specifically designed to assess the success of eleventh-grade pupils in the "Nuclear Physics" unit. We evaluated the test on a scale of 100 points with a confidence level of 0.91. Pupils received one point for each correct answer and zero points for each incorrect response. In this study, the pre-test reliability coefficient for the "Nuclear Physics Success Test" was 0.91, and the post-test reliability coefficient was 0.17.

H. Motivation Scale for Learning Physics

To gauge pupils' motivation for learning physics, we used the "Pupils' Motivation to Physics Learning (PMPL)" scale. The scale exhibited a reliability coefficient of 0.97 in the adaptation study, indicating its suitability for research. For this research, the reliability coefficient for the pre-test was calculated as 0.92, and for the final test, it was calculated as 0.99.

IV. Research Procedures

A. Pre-Application of Research Tools

The pre-application phase of research tools for Augmented Reality (AR) in education involves careful planning, selection, and preparation to ensure the effectiveness of the study. We clearly articulated the objectives and goals of the research. We specified what we aim to achieve by integrating augmented reality into the educational context. We conducted a thorough literature review to understand existing research on the use of augmented reality in education. Identify gaps, challenges, and best practices that can inform our study. We chose appropriate AR tools based on the educational objectives and the context of our study. We determined the technological requirements for implementing AR in the educational setting. We considered the accessibility of AR tools for all participants. We ensured that the technology does not create barriers for certain groups of students and that it is inclusive in catering to diverse learning needs. We conducted pilot testing of the selected AR tools in a smaller, controlled setting. This allows us to identify potential issues, refine procedures, and ensure that the tools align with the educational objectives. We provided training sessions for educators and students on how to use the selected AR tools. We ensured that participants are familiar with the technology and feel confident in its application. We addressed ethical considerations related to the use of AR in education. This includes obtaining informed consent from participants, ensuring data privacy, and considering the potential impact on participants. We developed a comprehensive plan for data collection. We clearly defined the metrics and parameters we will be measuring to assess the impact of AR on learning outcomes. We established a baseline assessment to measure the initial knowledge, skills, or attitudes of participants before the introduction of AR. This provides a basis for comparison in evaluating the effectiveness of AR.

B. Experimental Conduct

As illustrated in Fig. 3 the experimental groups received instruction with the assistance of AR applications aligned with the daily lesson plans prepared by the researchers, while the control groups received instruction solely in accordance with the daily plans. Prior to the commencement of the study, the 'Nuclear Physics Success Test' and 'Pupils' Motivation to Physics Learning' scales were administered as pre-tests to Experimental (1) and Control (1) groups. Subsequently, post-tests were administered to all groups at the conclusion of the research.

C. Post-application of Research Tools

The post-application phase of research tools for Augmented Reality (AR) in education involves analyzing collected data, drawing conclusions, and reflecting on the effectiveness of AR tools in achieving educational objectives. In post-application phase, we will utilize appropriate statistical methods to analyze the collected data. This may include quantitative analysis of pre- and post-assessment scores, survey responses, and other relevant metrics. We will assess the quantitative data to determine if there are statistically significant differences between the control and experimental groups. We will consider using descriptive statistics, inferential statistics, and other relevant methods. We will analyze qualitative data, such as feedback, observations, and open-ended survey responses. Identify recurring themes, patterns, and insights that provide a deeper understanding of participants' experiences with AR. We will compare the post-intervention data with the baseline assessment to evaluate the overall impact of AR on participants' knowledge, skills, or attitudes. We will calculate effect sizes to measure the practical significance of observed differences. Effect sizes provide context for the magnitude of the impact of AR on learning outcomes. We will interpret the findings in the context of the research objectives. We will identify any patterns or trends in the data that could inform future research or implementation strategies. Recognize both the successes and challenges encountered during the study. We will compare the research findings with existing literature on AR in education. Consider how your results align with or contribute to the current knowledge base. We will reflect on the implementation of AR in the educational setting. We will reflect on the validity and reliability of the study. We will assess whether the research design effectively measured what it intended to measure and if the results are dependable.

Also, we will reflect on the ethical aspects of the study, including participant consent, data privacy, and any ethical dilemmas encountered during the research process. We will consider the generalizability of findings to other educational contexts. Finally, we will evaluate whether the results are specific to the studied population or if they can be applied more broadly. We will share the research findings through academic publications, presentations, or other dissemination channels. Contribute to the broader knowledge base in the field of AR in education. In the post-application phase, researchers can contribute valuable insights to the understanding of AR's impact on education, informing future research, implementation strategies, and educational practices.

V. Results

The researchers employed several statistical procedures to analyze the data collected in the research. Cronbach's alpha coefficient was used to calculate the reliability of the scales, ensuring that the scales used in the study produced consistent and dependable results. To assess the homogeneity and normality of the data got from the scales, several tests were used, including the Levene Test, the Shapiro-Wilk test, and the examination of skewness and kurtosis. We employed this statistical procedure to determine the independent and combined effects of the pre-test and the experimental process on the collected data. This analysis was used to evaluate the interaction between the pre-test and post-test in the groups that received a pre-test. ANCOVA was used to determine the effect of covariates (in this case, pre-test scores) on post-test results. We used the Standard Physics test to identify specific groups where statistically significant differences were observed. Eta Squared (η^2) value was calculated to measure the effect size of statistical significance. We performed all data analyses using the SPSS 27 package program. These statistical procedures helped the researchers draw meaningful conclusions from the research data. In the data analysis process, one of the initial steps involved examining whether the data met the basic assumptions required for parametric tests. We did this to determine which specific statistical tests would be most appropriate for the data. To assess the homogeneity of variances, we performed the Levene test, as shown in Table 6. The helped in deciding how to proceed with the data analysis.

Table 6. Consistency test results for pre-test and post-test of experimental and control groups

Measuring instrument	Test Type	Levene Test	df1	df2	*p*
NPST	Pre-Test	4.60	2	71	0.05
	Post-Test	3.51	5	135	0.07
PMPL	Pre-Test	0.07	2	79	0.71
	Post-Test	0.65	5	139	0.61

In Table 6, it is evident that the variances of both the pre-test and post-test success scores for the experimental and control groups exhibited homogeneous distributions (Pre-test, F = 4.50, $p > 0.05$; Post-test, F = 3.61; $p > 0.05$). Similarly, the variances of the pre-test and post-test motivation scores for these groups also displayed homogeneous distributions (Pre-test, F = 0.03; $p > 0.05$; Post-test, F = 0.57; $p > 0.05$). We found the data to meet the assumption of homogeneity in terms of success and motivation variables based on variance analysis. Subsequently, the assumption of normality, another requirement for parametric tests, was assessed. In this research, normality analysis was conducted by examining the Skewness and Kurtosis values. We considering that testing the normality assumption, Skewness and Kurtosis values should be taken into account. We decided that Skewness and Kurtosis values within the range of + 1.5 to − 1.5 are acceptable. The Skewness and Kurtosis values for the pre-test and post-test measurement scores in this research are presented in Table 7.

Table 7. Skewness and kurtosis for pre-tests and post-tests of experimental and control groups

Test	Groups	Skewness	Kurtosis
Pre-Test	Experimental (1)	+1.1	–1.1
	Control (1)	+0.9	–1.3
Post-Test (1)	Experimental (2)	+1.1	–1.0
	Control (2)	+1.2	–1.0
Post-Test (2)	Experimental (3)	+1.0	–1.0
	Control (3)	+1.3	–0.9

In statistical analysis, skewness and kurtosis are two measures that help assess the shape and distribution of data. They provide insights into whether a dataset follows a normal distribution or deviates from it. Skewness measures the asymmetry of the data distribution. A positive skewness value shows that the data is skewed to the right, meaning it has a longer tail on the right side and is concentrated on the left. Conversely, a negative skewness value suggests a leftward skew, where the data is concentrated on the right and has a longer tail on the left. In this case, the values of skewness for this research groups indicate how much, if at all, the data deviates from a symmetric, bell-shaped distribution. Kurtosis measures a distribution, showing whether the data has heavier or lighter tails compared to a normal distribution. Positive kurtosis values suggest a distribution with heavier tails, showing more extreme values (leptokurtic), while negative values indicate lighter tails, meaning fewer extreme values. In this research, we examined the values of skewness and kurtosis for the data collected from the research groups to determine if they met the assumptions of normality. We made decision to use parametric tests (tests that assume a normal distribution) because these values fell within the acceptable range of +1.5 to −1.5 This suggests that the data followed a reasonably normal distribution and allowed for the use of parametric statistical tests. If the values were significantly outside this range, it might show a non-normal distribution, requiring non-parametric tests or data transformation. Table 7 provides the Skewness and Kurtosis values for the data collected from the research groups. Based on the determined values, we concluded that parametric tests should be employed. We made this decision because all datasets fell within the acceptable range of +1.5 to −1.5, indicating a normal distribution of the data.

The first question in this study aims to investigate whether there is a significant difference between pupils in the experimental and control groups regarding academic success and motivation when the experimental procedure and pre-test stimulation are taken into account. This question addresses both the independent and combined effects of the experimental procedure and the pre-test. To analyze this, we use a statistical technique known as "Two-way Analysis of Variance" for independent measurements. In Table 8, we present the arithmetic average (mean) and the standard deviation of the "Nuclear Physics Success Test (NPST)" post-test scores for the research groups. The mean provides information about the central tendency of the scores, while the standard deviation measures the dispersion or spread of the scores. This analysis allows we to compare the post-test scores between the experimental and control groups and assess whether any differences are statistically significant. Two-way ANOVA considers two independent variables, in this case, the experimental procedure (presence or absence) and the pre-test stimulation (presence or absence). It helps determine whether these variables, individually or in combination, have a significant effect on the post-test scores related to academic success and motivation. The results will indicate whether there are statistically significant differences between the groups and will help address the first research question as shown in Table 8.

Table 8. Mean and standard deviation for the NPST post-test scores of experimental and control groups

Data gathering instrument	Group	N	$\bar{X}$	SD
NPST	Experimental (1)	30	91.51	15.41
	Control (1)	30	83.03	18.63
	Experimental (2)	30	97.95	17.73
	Control (2)	30	75.19	15.19

In Table 8 we provided the average post-test scores ($\bar{X}$ post-test) for the Nuclear Physics Success Test (NPST) for each of these research groups. The Experimental Group (1) had an average post-test score of 91.51, while the Control Group (1) had an average post-test score of 83.03. Similarly, Experimental Group (2) had an average post-test score of 97.935, and Control Group (2) had an average post-test score of 75.19. Subsequently, we conducted a two-way analysis of variance for the NPST post-tests of this research groups, as presented in Table 9. This analysis examines the impact of two independent variables on the post-test scores: the experimental procedure (presence or absence) and the pre-test stimulation (presence or absence). ANOVA assesses whether there are significant differences in the post-test scores between these groups. The results will help us determine whether the experimental procedure, pre-test stimulation, or their interaction significantly affect the NPST post-test scores. This information is crucial for addressing this first research question regarding academic success and motivation in the experimental and control groups after applying the experimental procedure and pre-test stimulation.

Table 9. Results of analysis for independent measurements for NPST post-test of experimental and control groups

Source of Variance	Sum of Square	df	Mean of Square	F	p	η^2
Pre-test (Control (1))	95.11	1	95.11	0.27	0.42*	0.001
Experimental Process (Experimental (1))	4572.11	1	4572.11	25.57	0.0003	0.19
Pre-test* Experimental Process (Experimental (2))	61.35	1	61.35	0.31	0.71*	0.003
Total	39910.55	117				

$^*p < 0.05$

Based on this analysis presented in Table 9, we found that pre-test stimulation, i.e., whether or not pupils received a pre-test before the experimental process, did not lead to a significant difference in the success (NPST) of the pupils in the research groups. The presence of a pre-test did not significantly impact the pupils' academic success. The analysis showed that there was a significant difference between the pupils in the experimental groups and the pupils in the control groups concerning academic success (NPST) post-test scores. The experimental process had a statistically significant impact on the pupils' academic success, and the effect size (η^2) showed that this impact was moderate. The Standard Physics test was conducted to determine which groups had significant differences in NPST post-test averages. The results showed that both Experimental Group (1) and Experimental Group (2) had significantly higher post-test averages compared to both Control Group (1) and Control Group (2). We found that the experimental procedure and pre-test did not have a significant combined effect on pupils' academic success. Teaching the course with AR applications in the experimental groups had a positive and statistically significant impact on increasing the success of the pupils. These findings support the effectiveness of AR-enhanced teaching materials in physics education. Now, we are moving on to examine the post-test scores of pupils' motivation for physics learning, which is presented in Table 10.

Table 10. Mean and standard deviation of post-test PMPL scores of the experimental and control groups

Data collection instrument	Group	N	$\bar{X}$	SD
PMPL	Experimental (1)	30	251.50	15.11
	Control (1)	30	231.66	19.71
	Experimental (2)	30	261.51	19.09
	Control (2)	30	270.11	16.97

The data presented in Table 10show the post-test scores for pupils' motivation for physics learning (PMPL) in the different groups. We then conducted a two-way analysis of variance (ANOVA) to assess the statistical significance and the effects of different variables on the motivation scores of these groups, which is shown in Table 11 Similar to the results for academic success, the analysis reveals that pre-test stimulation, i.e., the presence or absence of a pre-test, did not have a significant impact on pupils' motivation for physics learning in the research groups. The analysis showed that there was a significant difference in pupils' motivation for physics learning (PMPL) post-test scores between the pupils in the experimental groups and those in the control groups. This means that the experimental process, which involved teaching with AR applications, had a statistically significant effect on improving pupils' motivation for learning physics. The effect size (η^2) suggests that this effect was of moderate magnitude. We conducted a Standard Physics test to determine which specific groups had significant differences in their motivation post-test averages. The results show that the motivation post-test average of Experimental Group (1) was significantly higher than Control Group (1). The motivation post-test average of Experimental Group (2) was significantly higher than Control Group (2). Similar to the findings for academic success, we concluded that the combined effect of the experimental procedure and pre-test did not significantly impact pupils' motivation for physics learning. The study shows that teaching the physics course with AR applications in the experimental groups not only had a statistically significant positive impact on pupils' academic success but also significantly improved their motivation for learning physics. This supports the efficacy of integrating AR-enhanced teaching materials in physics education.

Table 11. Results of independent measurement of post-test PMPL scores of the experimental and control groups

Source	Sum of Square	df	Means of Square	F	p	η^2
Pre-Test (Control (2))	33.12	1	33.12	0.089	0.69*	0.00
Experimental procedure (Experimental (2))	3,951.15	1	3951.15	10.91	0.0003	0.08
Pre-test *Experimental Intervention (Experimental (1))	512.01	1	512.01	1.216	0.08*	0.05
Total	21,154.55	119				

$^* p <> 0.05$

As stated in Table 11, there were no significant disparities in the PMPL (Pupils' Motivation to Physics Learning) averages between the groups that underwent pre-testing and those that did not (F (1,216) = 0.08; $p > 0.05$). In simpler terms, subjecting pupils to a pre-test before the experimental intervention did not yield noteworthy distinctions in the motivation levels of pupils in both the experimental (1) and control (1) groups. e employed a Standard Physics test to pinpoint the groups with significant differences. As a result, the post-test average motivation score of Experimental Group (1) ($\bar{X}$ = 245.35) was significantly higher than Control (1) ($\bar{X}$ = 265.54) and Control (2) ($\bar{X}$ = 114.87) groups (p <0.05). Similarly, the PMPL scale post-test average of Experimental group (2) ($\bar{X}$ = 260.57) surpassed that of Control (1) group ($\bar{X}$ = 124.75) (p < 0.05). In summary, these findings show that each experimental group exhibited distinct motivation post-test averages when compared to the control groups. There were no discernible differences between the motivational post-test averages of the experimental group (1) ($\bar{X}$ = 260.50) and Experimental Group (2) ($\bar{X}$ = 260.57). Notably, there were no distinctions observed between the motivational post-test averages of Control (1) ($\bar{X}$ = 2601.71) and Control (2) ($\bar{X}$

= 260.97) groups ($p > 0.05$). These results underscore the efficiency of teaching the course with AR applications to enhance pupils' motivation., It was established that the experimental procedure and pre-testing did not yield a significant combined effect on pupils' motivation (F (1,119) = 1.97; $p > 0.05$).

The second research question aimed to assess the impact of the experimental procedure on groups that underwent pre-testing. It sought to determine whether the experimental process had a significant effect on groups that received a pre-test. To address this question, we conducted two-way analysis of variance for mixed measurements was to investigate whether the scores of the Experimental (1) and Control (1) groups significantly differed before and after the experimental procedure. Initially, we examined the mean and standard deviation values of the Nuclear Physics Success Test (NPST) pre-test, post-test, and the difference scores for both the Experimental (1) and Control (1) groups.

Table 12. The mean and standard deviation for the NPST pre-test, post-test, and difference of experiment (1) and control (1) groups

Data collect tool	Gr.	N	Pre-Test		Post-Test		Difference Score	
			$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
NPST	Ex.	30	51.18	15.98	91.31	11.1	41.17	11.1
	Cont.	30	53.71	-45.17	53.97	17.55	31.35	15.3

The results presented in Table 12 show that, prior to application, the Nuclear Physics Success Test (NPST) score for Experimental Group (1) had a mean of $\bar{X}_{\text{pre-test}} = 51.18$, and after the application, it increased to $\bar{X}_{\text{post-test}} = 91.31$. Similarly, before the experimental process, the academic success score for Control Group (1) had a mean of $\bar{X}_{\text{pre-test}} = 53.71$, and after the application, it rose to $\bar{X}$ post-test = 53.97. The difference between the post-test score and the pre-test score for Experimental Group (1) was $\bar{X}_{\text{post-test}} - \bar{X}_{\text{pre-test}} = 41.17$, while in Control Group (1), this difference was $\bar{X}_{\text{post-test}} - \bar{X}_{\text{pre-test}} = 31.35$. Subsequently, we conducted a two-way analysis of variance for mixed measurements to examine the academic success results

As stated in Table 13, a significant difference was observed in the Nuclear Physics Success Test (NPST) scores between the experimental groups that received lessons with Augmented Reality (AR) applications and the control groups that only had lessons based on the standard program's activities. The increase in the scores of the experimental group after the experimental intervention was significantly higher than that of the control group (F (1,58) = 5.65; $p < 0.05$). The difference scores favored the experimental group, with a difference of $\bar{X}_{\text{post-test}} - \bar{X}_{\text{pre-test}} = 39.15$ for the Experimental Group (1) and $\bar{X}_{\text{post-test}} - \bar{X}_{\text{pre-test}} = 31.11$ for the Control Group (1). This suggests that supplementing the program's activities with AR applications had a significant effect on pupils' success in the "Atom System" subject, and this effect was of moderate magnitude ($\eta^2 = 0.06$). Given that the study aimed to test the effectiveness of AR applications in enhancing pupils' success, the combined effects of measurement and the experimental process were emphasized. We also examined the main effects of measurement and the experimental process. It was found that there was a significant difference between the total scores of the post-test and pre-test for both the experimental and control groups (F (1,59) = 7.55, $p < 0.05$). This suggests that supplementing the program's activities with AR applications increased pupils' success and had a moderate effect ($\eta^2 = 0.08$, A significant difference was observed between NPST post-test and pre-test scores for all pupils in both the Experimental (1) and Control (1) groups, without distinguishing between groups (F (1,57) = 303.15; $p < 0.05$). This shows that pupils' success significantly improved throughout the experimental process, regardless of the activities applied, and this increase had a substantial effect ($\eta^2 = 0.78$). Next, we examined the mean and standard deviation values for the Pupils' Motivation to Physics Learning (PMPL) pre-test, post-test, and difference scores of Experimental (1) and Control (1) groups (Table 14).

Table 13. Mixed measurements for NPST pre-test and post-test for experimental and control groups

Variance	Sum of Square	df	Mean of Square	F	*p*	η^2
Factors	31542.90	58				
Experimental process (expr)	3214.10	1	3214.10	4.66	0.03*	0.08
Subjects Factors	51262.10	60				
Difference in pre-test and post-test (expr)	35124.30	1	35124.30	230.15	0.002*	0.71
Difference in pre-test and post-test (cont.)	830.02	1		6.5	0.03*	0.06
Experimental process (cont.)	850.05					
Total	85570.90	120				

*$p < 0.05$

Table 14. Measurements for PMPL pre-test and post-test for experimental (1) and control (1) groups

Variance	Sum of Square	df	Mean of Square	F	*p*	η^2
Factors	41542.90	58				
Experimental process (expr)	4214.10	1	4214.10	4.66	0.03*	0.09
Subjects Factors	61262.10	60	61262.10			
Difference in pre-test and post-test (expr)	35124.30	1	35124.30	230.15	0.002*	0.81
Difference in pre-test and post-test (cont.)	930.02	1		6.5	0.03*	0.05
Experimental process (cont.)	950.05					
Total	95570.90	120				

*$p < 0.05$

A two-way ANOVA for mixed measurements was then performed to assess pupils' motivation for learning p hysics, and we present the results in Table 15.

Table 15. Measurements for PMPL pre-test and post-test for Experimental (1) and Control (1) groups

Source of Variance	Square	df	Mean of square	F	*p*	η^2
Factors	31097.40	59				
Experimental process	4532.61	2	4532.61	15.31	0.0002	0.17
Subjects Factors	152325.1	58				
Difference in pre-test	290.01	2	340.03	2.04	0.17*	0.04
Difference in pre-test and post- test	210.78	2	210.78	0.79	0.41*	0.02
Total	49568.60	118				

*$p < 0.05$

Table 15 reveals that the PMPL scores of the experimental groups, which were taught using AR applications, and the control groups, which followed the planned program activities, did not exhibit a significant difference after the experimental intervention (F = 15.31; $p > 0.05$). When considering the difference scores for the pre-test groups, it is apparent that both groups experienced relatively small changes in their motivation scores after the application. Several factors could contribute to this outcome, such as the initially high motivation levels, the pupils' familiarity with the researcher, and the challenge of altering affective variables like motivation within a short six-week period. Although the difference was not statistically significant, the increase in difference scores within the experimental group suggests that AR applications had a positive influence on pupils' motivation. The overall difference between the sum of the post-test and pre-test PMPL scores for the experimental and control groups was significant (F = 0,79; $p < 0.05$). Based on this result, we can conclude that augmenting the planned program's activities with AR applications had a substantial impact on PMPL and reflected a notable effect ($\eta^2 = 0.17$). there was no significant difference between the PMPL post-test scores and pre-test scores for all pupils in the Experimental (1) and Control (1) groups, without distinguishing between groups (F = 0.41; $p > 0.05$). We can attribute this lack of difference to the minimal change between the sum of the post-test scores and pre-test scores for groups that received the pre-test. As previously mentioned, altering affective variables like motivation within a brief timeframe can be challenging, and the pupils' pre-existing motivation in physics lessons may also have contributed to the absence of significant differences.

The third research question aimed to investigate whether the experimental procedure made a significant difference in the academic success and PMPL post-test scores of pupils in the pre-test groups when the pre-test was controlled. It sought to determine the effectiveness of the experimental process while considering the pre-test scores of the Experimental (1) and Control (1) groups. To analyze this, we performed Single Factor Covariance Analysis. In this covariance analysis, the pre-test was treated as the control variable to assess its impact on the dependent variables, which were the post-test success scores. By controlling the pre-test, the study aimed to isolate and identify the true effect of the experimental process. We conducted the covariance analysis, taking into consideration the homogeneity and normal distribution of pre-test and post-test success scores for both Experimental (1) and Control (1) groups. It was also confirmed that there was a linear relationship between pre-test success scores (the control variable) and post-test success scores (the dependent variable), with equal slopes for the regression lines. The post-test scores, adjusted based on the pre-test scores, are presented in Table 15.

Table 16. Revised mean considering NPST pre-tests of Experimental (1) and Control (1) groups

Group	N	Mean	Corrected Mean
Experimental (1)	30	80.56	97.57
Control (1)	30	80.74	98.96

Table 16 shows that when the effect of the pre-test was controlled, the average success score of Experimental Group (1) increased from 80.56 to 97.57, while the success score of Control Group (1) increased from 8074 to 98.96. The results of the covariance analysis aimed at determining whether the differences between the adjusted average scores of the groups were significant are presented in Table 17.

Table 17. ANCOVA for the post-test scores of NPST of the experimental (1) and control (1) groups

Source of Adjustment	Sum of Square	df	Mean of Square	F	p	η^2
Pre-test	5177.16	1	5177.16	15.17	0.0001*	0.19
Experimental process	4112.33	1	4112.33	11.35	0.0001*	0.17
Total	9289.49	60				

*$p < 0.05$

According to the results of the covariance analysis presented in Table 17 we found that when the NPST pre-test scores were held constant, there was a significant difference between the post-test scores of Experimental Group (1) and Control Group (1) (F = 11.35; $p < 0.05$). These findings suggest that teaching the course with AR applications has a substantial effect on increasing pupils' success, with an effect size (η^2) of 0.16. When examining the impact of the control variable to account for the experimental process, it was observed that there is a significant relationship between pre-test and post-test scores (F = 15.17; $p < 0.05$). Subsequently, in the covariance analysis, we determined that the pre-test and post-test PMPL scores of Experimental Group (1) and Control Group (1) exhibited homogeneous and normal distributions. We established that there was a linear relationship between pre-test PMPL scores and post-test PMPL scores, with equal regression line slopes.

The post-test scores, adjusted based on pre-test scores, for both Experimental Group (2) and Control Group (2), are provided in Table 18.

Table 18. Adjusted mean considering pre-tests of PMPL of experimental (2) and control (2)

Group	N	Mean	Corrected Mean
Experimental (2)	30	157.13	155.15
Control (2)	30	171.52	180.05

As stated in Table 18, after accounting for the influence of the pre-test, the PMPL average of Experimental Group (2) decreased from 157.13 to 155.15. In contrast, the PMPL average of Control Group (1) increased from 171.52 to 180.05. The results of the analysis of covariance, which was conducted to determine if the differences between the adjusted average scores of the groups were statistically significant, are presented in Table 18.

The covariance analysis results presented in Table 19 show that, when the PMPL pre-test scores were held constant, we observed a significant difference d between the post-test scores of Experimental Group 1 and Control Group 1 (F = 9.51; $p < 0.05$). This implies that teaching the course with AR applications has a moderate effect on increasing pupils' motivation, with an effect size (η^2) of 0.19. When investigating the control variable's impact on control for the experimental process, we found that there is a significant relationship between pre-test and post-test scores (F = 7.01; $p < 0.05$).

Table 19. ANCOVA for PMPL scale on corrected post-test of experimental (1) and control (1) groups

Variance	Sum of Square	df	Mean of Square	F	*p*	η^2
Pre-test	2154.91	1	2154.91	7.01	0.03*	0.20
Experimental procedure	1953.12	1	1953.12	9.51	0.02*	0.19
Total	4125.03	59				

*$P < 0.05$

Cronbach's alpha coefficient is a measure of internal consistency reliability, commonly used in educational research to assess the reliability of a scale or set of items. It indicates the extent to which we correlate items within a test or measurement instrument, reflecting the reliability or consistency of the measurements. In augmented reality education, Cronbach's alpha can evaluate the reliability of surveys, questionnaires, or assessments designed to measure various aspects of the educational experience. We used Cronbach's alpha during the development of questionnaires related to AR in education. This helps ensure that the items within the survey are internally consistent and measure the intended constructs reliably. In AR education, researchers may design instruments to measure constructs such as pupils' perceived usefulness of AR, their satisfaction with AR-based activities, or the impact of AR on learning outcomes. Cronbach's alpha assesses the internal consistency of these measures. Researchers may use Cronbach's alpha to validate the reliability of scales designed to evaluate different dimensions of AR education, such as usability, engagement, or learning effectiveness. Cronbach's alpha is sensitive to the number of items at scale. We balance having enough items to ensure comprehensive measurement and avoiding unnecessary redundancy. Item analysis can help refine the scale for optimal reliability. Cronbach's alpha value of close to 1.0 shows high internal consistency, suggesting that it highly correlated the items within the measurement instrument. A value below 0.7 may indicate lower reliability, and researchers may need to reconsider or revise the items. Cronbach's alpha is used at different stages of the research process, from the initial development of instruments to subsequent iterations. It is beneficial for continuous assessment and improvement of measurement tools. We used Cronbach's alpha to compare the internal consistency of measurement instruments across different participants, such as pupils with varying levels of AR exposure or experience. Cronbach's alpha is a valuable statistical tool in AR education research for assessing the reliability of measurement instruments. It ensures that the data collected through surveys or questionnaires accurately and consistently reflects the intended constructs, contributing to the validity of research findings in augmented reality education.

VI. Discussion

The analysis results shows that pre-testing did not yield a significant effect on the academic success and motivation levels of the study groups. In a separate mixed study examining the influence of microteaching on the development of pedagogical subject knowledge among physics teacher candidates, we adopted a quantitative approach based on the Solomon four-group experimental model [33]. The findings revealed that pre-testing did not exert a significant influence on the outcomes [34]. In an experimental study employing the Solomon four-group experimental model, we explored the impact of teaching the subject through digital games in a social studies course on academic success [35]. The results showed a significant difference between the scores of the experimental and control groups, with pre-testing exhibiting no substantial influence. In another study using the Solomon method to evaluate game-based learning, the aim was to find out the advantages and disadvantages of pre-testing. The results showed that the pre-test had no substantial effect, while game-based learning proved effective. It's worth noting that the pre-test groups showed higher means compared to those without pre-testing, and we should take this finding into consideration in future studies. Although no significant differences were observed between the study groups in terms of pre-testing, it becomes clear that the scores of the groups that underwent pre-testing stimulation was higher when considering the final test scores of the pupils [36]. This phenomenon can be attributed to pupils' familiarity with the structure and format of the questions, which may have boosted their performance. We reviewed previous studies in our country that used Solomon's Four-Group Model and found that there was a lack of clear guidance on the statistical procedures required for analyzing data within this experimental framework [37]. To address this gap, we turned to international studies that provided detailed descriptions of Solomon's Four-Group Models. In this research, we rigorously analyzed data collected using Solomon's Four-Group Model and attempted to convey each step clearly to the reader. Incorporating Solomon's four-group model, which enables the determination of whether pre-test effects are statistically significant, has enhanced both the internal and external validity of our study [38]. The absence of pre-test effects suggests that changes in pupils' academic success and motivation are attributed to the impact of AR technology. Through the application of a two-way analysis of variance to assess the impact of the experimental process, we observed that the utilization of AR applications during the course had a positive influence on pupils' academic success [39]. This favorable outcome can be partly attributed to pupils' exposure to a novel technology, their fascination with this technology, and the perception of magic when AR technology brings objects to life in three dimensions. Previous studies have also reported similar findings, demonstrating that the use of AR enhances pupils' academic success. We reported that the use of AR applications in the eleventh-grade physics class during the "Atom System" unit led to improved academic success among pupils [40]. We conducted a quasi-experimental study, which showed that AR applications positively affected pupils' academic success. We reported that AR-supported learning environments increased pupils' academic success and motivation levels. In an investigation focused on the influence of mobile AR applications on the academic success and cognitive load of medical pupils, we found that the experimental group outperformed the control group [41]. We reported that mobile-supported AR applications augmented academic success and motivation levels, and we underscored the effectiveness of AR in enhancing academic achievement. Our research also revealed that AR-based training enhances spatial memory by offering an interactive interface that facilitates superior learning of anatomy. We can achieve the translation of knowledge gleaned from these educational studies through interactive environments presented to pupils via AR applications. Technologies integrated into education captivate pupils' attention, engage them in the learning process, heighten their involvement and motivation, and facilitate a better understanding of the subject [42]. Notably, the new 2023 Physics Education Program places a heightened emphasis on the domains of the world and the universe as the initial units of study. In the past, this unit often received insufficient attention, mainly because of its position as the final unit before the upcoming summer holiday. Implementing the activities outlined in the program for this unit also posed challenges, primarily because pupils lacked a suitable learning environment for observing celestial objects [43].

Textbooks fall short for providing a three-dimensional visualization of the atom system. The conventional teaching of physics, often conducted within enclosed spaces, may pique pupils' interest, but its effectiveness is questionable. In this research, the use of AR applications successfully achieved a three-dimensional visualization of astronomical phenomena that would typically challenge to present in a standard classroom setting [44]. This, in turn, facilitated easier learning by establishing a spatial connection between these concepts, aligning with the cognitive development stage of eleventh-grade pupils. When considering the impact of the experimental process on pupil motivation, it becomes clear that instruction with AR applications significantly influences pupil motivation. Literature supports the notion that AR-enhanced learning heightens pupil motivation, with pupils expressing enjoyment in using such applications [45]. Previous studies have showed positive effects on motivation when AR technology is incorporated into various subjects. For instance, researchers found the use of AR technology in teaching English vocabulary to positively affect pupil motivation. Similarly, integrating AR into visual arts lessons increased pupil attention, motivation, and interaction with the learning environment. Research has also showed that employing AR technology in foreign language teaching books enhances pupil motivation for vocabulary learning [46]. Prospective physics teachers using AR technology in their classes reported improved learning environments, increased pupil motivation, and greater ease of application. The AR technologies used in the study have some limitations. These limitations primarily concerning issues related to tracking, hardware, connectivity, and ongoing improvements [47]. Efforts are underway to address these limitations. Notable drawbacks include late object detection by the camera, camera freezing, and, most significantly, excessive power consumption while the application is active. Addressing these technical challenges requires both human resources and time. However, despite these limitations, the rapid development of digital and mobile technologies in recent years offers the potential to bridge these gaps. Another limitation observed in the study is that, for the applications to function effectively and allow each pupil to observe objects in three dimensions, the experimental groups required a longer study period than the control groups [48]. The reason for this discrepancy may be twofold: pupils in the experimental group wished to view the atom system in three dimensions more than once, and there was a necessary time lag for the technological tools to operate and for AR applications to recognize objects. It can be affirmed that modern technology has made mobile devices, such as smartphones and tablets, particularly well-suited for augmented reality (AR) experiences [49]. These devices offer several advantages, including portability, widespread usage, easy re-chargeability, and access to software repositories like the Play Store and Apple Store. When we look at the evolution of mobile devices from the past to the present, it is reasonable to expect the production of even more powerful mobile devices soon. This suggests that new AR applications are likely to be developed, making mobile AR applications a valuable resource for educators [50]. Within this context, educators can make innovative choices in the classroom, incorporating AR applications alongside traditional tools like textbooks, whiteboards, and chalk [51]. AR technology can benefit pupils, especially those with weaker visual perception, by enhancing their three-dimensional thinking skills. AR technology constructs real images of virtual objects, transforming static objects into multimedia elements, enhancing the functionality of the learning environment [52]. The increasing diversity of educational technologies places an important responsibility on educators to recognize and effectively use them [53]. Educators should keep abreast of technological advancements and select the most appropriate tools for their respective fields. The existing body of literature in this field reveals a growing awareness among teachers, particularly regarding the use of AR technologies in education, alongside a rising number of research studies [54]. Drawing from this study and similar ones as references, conducting further studies on various subjects and courses will be crucial in demonstrating the effectiveness of this technology in education. Considering the adaptability of mobile AR applications for teaching other subjects within the realm of the physics course, this technology could prove valuable for instructing other units that are similarly challenging to visualize [55]. To fully harness the potential of AR applications, school physical environments should facilitate their optimal use, and classrooms should be equipped with the tools and equipment for this technology. It is advisable to conduct studies with larger sample groups using different methods and variables to explore the effective usability of this technology [56]. Given that developed countries aspire to produce individuals who can rapidly adapt to, efficiently use, and even create technology, the successful integration of AR technology into educational environments and the assessment of its advantages and disadvantages through these studies will provide valuable insights for educators seeking to incorporate this technology into their teaching methods [57]. Teachers play a crucial role in the successful integration of Augmented Reality (AR) in learning physics. Teachers act as facilitators, guiding students through the AR-enhanced learning experiences [58]. They help students navigate the content, understand the context, and make connections between virtual and real-world physics concepts. Teachers design and plan instructional activities that incorporate AR elements. They create lessons that leverage AR to enhance understanding, engagement, and retention of physics concepts. Teachers integrate AR technology into the curriculum effectively. They need to be familiar with AR tools and platforms, ensuring that students can access and use them seamlessly. Teachers understand the diverse learning styles and needs of their students. They can adapt AR applications to cater to different learning preferences, ensuring that the technology meets individual student requirements. Teachers provide guidance and support as students engage with AR. They can answer questions, address concerns, and offer explanations, creating a supportive learning environment. Teachers help students contextualize AR experiences within the broader physics curriculum. They connect virtual content to real-world applications, reinforcing the relevance of physics concepts. Teachers assess students' understanding of physics concepts within the AR environment. They provide timely feedback to help students improve and make the most of their augmented learning experiences. Teachers assist students in solving problems that may arise during AR activities. They encourage critical thinking and help students navigate challenges related to both the physics content and the technology itself. Teachers play a vital role in motivating students to engage with AR-enhanced lessons. Their enthusiasm and encouragement can significantly impact students' interest in learning physics through AR. Teachers engage in ongoing professional development to stay updated on new AR technologies and teaching strategies. This ensures they can effectively leverage the latest tools for enhanced physics education. Teachers align AR activities with overall curriculum goals and standards. This ensures that AR is not a standalone element, but an integrated part of the broader educational framework. Teachers are essential in creating a meaningful and effective learning experience when incorporating AR into physics education. Their role goes beyond just delivering content; they guide, support, and inspire students to explore and understand the world of physics through augmented reality. From a methodological perspective, we recommended that further research be conducted to examine the effects of the pre-test and experimental procedure, particularly because of the limited number of studies using the Solomon four-group experimental model in physics education.

The research reveals a statistically significant improvement in students' academic success in physics following incorporating educational activities supported by augmented reality. Post-test scores shows a notable increase in the understanding and retention of physics concepts among students who experienced augmented reality-enhanced learning. Augmented reality offers a dynamic and interactive approach to teaching physics, providing students with immersive experiences that contribute to a deeper understanding of theoretical concepts. The visual and interactive nature of augmented reality helps students visualize complex physics phenomena, making abstract concepts more tangible and accessible.

The hands-on engagement facilitated by augmented reality can lead to improved problem-solving skills and a more practical application of theoretical knowledge. Augmented reality emerges as a valuable tool for enhancing academic success in physics education. The findings suggest that integrating augmented reality into physics instruction could be an effective strategy for improving students' performance and comprehension.

The study shows a positive impact on students' motivation to learn physics when educational activities are supported by augmented reality. Surveys and qualitative data show increased interest, curiosity, and engagement among students who have experienced augmented reality-based learning. Augmented reality introduces an element of novelty and excitement into the learning process, capturing students' attention and fostering a more positive attitude toward physics. The interactive and immersive nature of augmented reality experiences enhances students' intrinsic motivation by making learning enjoyable and relevant to their experiences. Positive social interactions and collaborative learning opportunities within an augmented reality environment contribute to a supportive and motivating learning atmosphere. Augmented reality is not only a pedagogical tool but also a motivational catalyst, potentially addressing challenges related to student engagement and interest in physics. Educators should leverage augmented reality to create a more stimulating and motivating learning environment, ultimately fostering a love of physics. The research outcomes underscore the multifaceted benefits of incorporating augmented reality into physics education. Beyond academic success, the positive impact on students' motivation suggests that augmented reality has the potential to transform the learning experience, making it more engaging, enjoyable, and conducive to sustained interest in physics. These findings contribute to the growing body of evidence supporting the integration of augmented reality as an effective and motivational tool in physics education.

VII. Conclusion

In this study, AR applications are seen as effective tools to facilitate access to and visualization of complex physics concepts that can be challenging to grasp through traditional teaching methods. By using AR applications, pupils can delve into these concepts, explore the mysteries of the universe, and engage with elements that are typically beyond their physical reach. The conclusion of this research is that the use of augmented reality applications in physics education has a substantial positive impact on pupils' academic performance and motivation. However, it is important to note that this research specifically focused on physics topics, so its findings may not directly apply to all physics education. While augmented reality is a promising tool, it may not represent the ultimate solution. Future research could explore the integration of AR technology across various physics disciplines to gauge its broader impact on pupils' physics education and achievement. It provides valuable insights and encourage educators to explore the potential benefits of AR applications in their teaching practices. We are putting forth practical recommendations with the specific aim of harnessing augmented reality technology to improve the quality of physics education. We recommend making use of augmented reality technology to overcome problems in teaching physics. We suggest integrating augmented reality technology as a solution to address the challenges and obstacles faced by both pupils and teachers in the process of teaching physics. Implementing augmented reality might enhance the learning experience by providing interactive and immersive content, addressing deficiencies identified in the research. We recommend holding training courses for teachers and pupils on linking virtual reality with real reality. Recognizing the importance of effectively integrating virtual reality, specifically augmented reality, with real-world scenarios, the recommendation calls for training courses. Training courses can equip both teachers and pupils with the skills and knowledge needed to use augmented reality in the learning environment. This includes understanding how to connect virtual content with real-world applications.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Beken Arymbekov led comprehensive research efforts, including defining research topics, framing issues, and analyzing and interpreting data. He was responsible for designing interactive multimedia products and validating tools related to visual design and software usage. Kunduz Turekhanova contributed to the design of interactive multimedia and validated instruments within the realm of learning design. Mussa Turdalyuly played a pivotal role in creating multimedia prototypes, conducting one-on-one and small-group product trials, and overseeing the collection and processing of data. Beken Arymbekov also took charge of field tests, overseeing data collection and processing. The final version of the work received approval from all authors.

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DATA AVAILABILITY STATEMENT

All data supporting the findings of this investigation are included in the manuscript.

ETHICS DECLARATION

The authors confirm that formal ethics approval was not deemed necessary for this study, as the data collected were entirely anonymous, containing no personal information except for age and gender. Informed consent was obtained from all research participants.

ETHICAL STATEMENT

This study adhered to the principles of the Declaration of Helsinki. Approval for this human study was granted by the review board of the Department of Physics Education at the Satbayev University. Written informed consent was provided by parents, guardians, or next of kin for minors participating in the study, and written informed consent was obtained from all adult participants. Participants also consented to the publication of their results.

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