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Augmented reality in Physics education: A tool for intellectual learning

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Abstract

This study investigated the integration of augmented reality (AR) and virtual reality (VR) technologies in physics education, focusing on their potential to enhance teaching methods and address existing pedagogical challenges. A literature review, along with an experimental comparison of AR and VR-based instruction, was conducted to assess their impact on student engagement, comprehension, and retention. The findings indicated that AR significantly improved student participation and information retention, with students using AR-based resources demonstrating higher engagement and comprehension compared to those using traditional materials. The research also highlighted the need for teacher training in AR-based instruction and the value of student involvement in developing AR applications. By employing a combination of theoretical and practical teaching strategies, the study showed that AR could effectively support the visualization and problem-solving of complex physics concepts. Additionally, the study emphasized the broader applications of AR and VR technologies in fields such as medicine and engineering, suggesting the importance of continued research and investment to unlock their full educational potential while addressing accessibility challenges.

Keywords*:* Augmented reality; education; physics; virtual reality

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1. INTRODUCTION

Since the development of distance education and the development of information technology (IT), many problems have arisen in the educational process. At different times, any innovation in education is viewed with trepidation. In the 21st century, in the highly developed age of information technologies, it has become necessary to introduce them into the education system. Automated systems like e-diaries and e-journals cannot surprise anyone (Huba & Kozák 2016).

Computer technologies are used almost everywhere in the educational process, although the debate about the benefits and harms of computer games is still not decreasing. Many experts have noticed that the emotional appeal and the combination of audio-visual, informational, and computer capabilities characteristic of computer games have a great didactic potential that should be included in the learning process. If previously the teacher was the only information carrier in the classroom, with the development of gadgets, students began to receive information from their environment - friends, colleagues, and social networks. Currently, it is hard to imagine a world without gadgets (Nikou, 2024; Baygin et al., 2016).

Teachers who want to give students new knowledge and captivate them with their subject use all the possibilities of modern times (Laumann et al., 2024). IT technologies allow teachers not only to focus the student's attention but also to develop interest in the learning process and to form technological skills necessary for further academic education and professional career development (Villanueva et al., 2021; Koumpouros, 2024). In this article, the author presents an experiment aimed at determining the conscious interest in augmented reality tools for schoolchildren of different classes in Almaty. VR (virtual reality) is a set of technologies that can create an artificial world that does not exist physically but can be felt through the senses in real time according to the laws of physics (Demartini & Benussi 2017).

Created virtual objects and subjects affect people through technical means senses: a sense of smell, balance and position, space, touch, sight, taste, and hearing. "Virtual reality" systems are devices that fully simulate interaction with the virtual environment by affecting all five human senses, unlike conventional computer systems. Virtual reality simulates the effect and reaction of various objects to this effect. The first VR system was the Oculus Rift headset. The Oculus Rift virtual reality helmet came to the market according to all the canons of the high-tech genre of our time. It was not born within the walls of one of the IT giants like Google or Microsoft. On the contrary, Oculus is one of the most successful startups: within a month, the development of the American Palmer Lucky raised 2.5 million dollars on Kickstarter, and the young man himself even appeared on the cover of Time magazine. There are different types of virtual reality systems used in entertainment and scientific fields:

- Augmented – the virtual reality system does not disturb the usual view of the surrounding world, but it is only artificially supplemented by created elements (Ferrari et al., 2024).
- Blending - this is where bonding takes place, turning artificially created elements into real ones, creating a high level of realism.
- Virtual - all elements are a product of the developers' imagination or a simulated program. Immerse yourself in a fictional world with the help of special devices

1.1. Literature review

The history of augmented reality (AR) dates back to the middle of the 20th century when, for the needs of the military, they first began to create devices that allow viewing additional information in the operator's field of view. At this time, the development of educational games also began, and in 1955, the first computer game was created. The purpose of the game was to train US Air Force officers to manage the supply of air bases. The game was called "Imitation of decisions in the top management" and solved the actual problems in the technological development of large US companies. Since then, the functions of simulation games with production and economic simulations have been called "Business" or "Management" (Carroll, 2019).

The development of gaming culture in our country is primarily due to the name of Shargul Taubayeva. His method, which combines a rigidly structured approach and strong pressure on the personality of each participant, has been used to solve complex interprofessional problems.

At the same time, Kazakhstan conducted research related to the development of business games with motivational and educational video games and their potential (Fisk, 2020).

The results of a similar study in 1993 showed that players had better motor and hand-eye coordination, had less difficulty learning basic subjects, and found that educational video games can help students:

- correction of identified deficiencies;

- adapt the game to the student's interests, increase enthusiasm, and stimulate;

- improve concentration;

- immediate feedback (Kreijns et al., 2013).

One of the main reasons for using educational video games in the educational process is to gain practical experience without fear of making mistakes, and even vice versa - to be able to do it deliberately, showing the result in real-time (Udeozor et al., 2023). For example, such a system is used in the training of pilots, and the modern RED augmented reality system allows training pilots in the air combat system. In the mid-1980s. Simulation games are widespread in education and are included in biology, medicine, architecture, and ecology. But the events of those years considered only highly specialized issues, not predicting psychological impact. With the beginning of the mass introduction of personal computers, a new period of development of educational games began (Dror, 2008).

In 2010, Time magazine included augmented reality on the list of technologies used. Over time, large corporations began to implement the technology en masse for their purposes, but all of them are still quite expensive, so the technology is slow to spread. AR enriches the world with the latest technologies, creates audiovisual images, gives students a memorable opportunity to see the learning material in the classroom, and makes it vivid. The effectiveness of this teaching method has been proven by several tests and experiments (Martin et al., 2011).

For example, an experiment was conducted, during which the subjects of two groups were offered to receive the material in different ways. One group received visual material in the form of stands and posters, and the second group received visual material with AR. It was found that the group that received the materials using augmented reality accepted them at a rate of 90%, and the concentration of attention reached 95% of the entire audience, while the indicators of the group using two-dimensional materials were half as low (Bronack, 2011). The reason for the possibility of such indicators is that AR creates an immersive effect that shows the connection between the real and virtual world, which psychologically seems more attractive to a person and increases their tendency to accept new information (Milgram et al., 1995; Schöne et al., 2023).

Currently, the following types of systems are marked VR:

- Virtual reality helmet. 1) includes glasses and one or more displays for displaying images; 2) the system determines which tracks and the location of the helmet in space for tracking. Typically, tracking systems for virtual reality helmets are developed based on gyroscopes. For these types of systems, the accuracy of the tracking system is important when tracking tilts and turns to the user, as well as the minimum latency between tracking position changes and displaying heads in space and the corresponding image on the screens (Azuma, 1997). This type includes various technological devices, from smartphones and tablets to special VR rooms (CaveAutomaticVirtualEnvironment). Systems of this type provide the user with a sense of three-dimensional objects, along with help from projections of virtual objects based on the location of the user's eyes. When it changes, the relative user's eye position is displayed, and the image changes accordingly. These types of VR use a 3D imaging technology called Motion Parallax. The systems track the coordinates of the source in space. Optical cameras are used for this (Höllerer & Feiner 2004).

Virtual reality gloves. Students and engineers from the University of California, San Diego (UC San Diego), created gloves that allow you to feel a tactile response when interacting with virtual reality (Kaufmann, 2003). Soft robotics technologies were used to create the device. These gloves demonstrated the ability to realistically simulate tactile responses. Virtual keyboard when playing and using the piano. One of the authors of the project is Michael Tolley, now a professor of mechanical engineering at the School of Engineering (Zhou et al., 2008). Jacobs (Jacobs School of Engineering). According to him, the ultimate goal of the developers is to create a device that provides a "rich experience" of interacting with virtual reality. These gloves can be used not only for video games but also for surgery. Rosatom" JSC can be cited as an example of the use of virtual reality technologies in Russia. To efficiently build the power units of the nuclear power plant, they needed a tool that would allow them to optimize the construction process: conduct detailed modeling of the work plan, change the sequence of activities related to the delivery schedule of contractors, and subcontractors, and reduce the risks and consequences of delays (Yuen et al., 2011). Such a tool was a virtual reality system such as VE CADWall, which consists of a large flat screen and several projectors that display a single image in 3D at a scale of 1:1. The system provides interactive interaction control of a person's movement in front of a virtual scene, and the virtual suit and gloves allow him to interact with virtual objects: he elaborates the assembly processes in reality, ensures the connection, assembly, and interchangeability of parts.

In addition, a video conferencing system was integrated into the VR system for holding conferences and meetings at the construction headquarters. Currently, the system is used by Rosatom NPP for maintenance and control of the construction process, as well as training and familiarization of personnel. Virtual reality systems can be used effectively and are already being used in medicine. The doctor's reception of three-dimensional information about the patient (tomography, three-dimensional information of the X-ray machine, ultrasound) allows to significantly improve the quality of the work of doctors. Interactive models and the reconstruction of learning organs were used for the design of the surgical intervention. With the help of special software, doctors can create models of individual prostheses based on the patient's scan.

Creating simulators based on virtual reality technologies allows to significantly improve the quality of training of doctors, reduce costs, and reduce the number of medical errors (Dunleavy et al., 2009). Applications In electromagnetic, pneumatic, and hydraulic systems, you can simulate a virtual scalpel or another tool using command and control systems (such as a virtual glove and a system that simulates tactile sensations). Virtual reality gloves are planned to be used not only in video games and digital entertainment but also in surgery. Experiments on virtual cadavers are cheaper than real ones and more humane than testing on animals. Many complex operations (for example, plastic surgery) require careful planning and preliminary modeling of the doctor's actions. Medical simulators allow you to completely "lose" the course of the operation, identify difficult areas, and prepare for various scenarios.

The use of VR and AR technologies for corporate purposes is becoming the norm, which allows for more cost-effective and productive training of employees and processing of complex and non-standard situations. Now, you can remove the geo-binding location. Volvo's use of a unique AR advertising application resulted in a 293% increase in company website traffic, an 88% increase in purchase intent, and a 240% increase in brand awareness. Due to the game format of the application, it was possible to attract the attention of a young audience - potential owners of Volvo cars. Can you sell cars with VR? The experiment is actively being conducted. Ekaterinburg company U360 developed a 360° video for local Jaguar dealer Autoplus. A person wearing virtual reality glasses at home or a Samsung Gear VR helmet at a car dealership wants to drive a car, "ride" with the wind, and enjoy the interior and the dashboard. Car brands experiment with panoramic video everywhere; Jaguar's 360° test drive was also filmed in Taiwan (Kye & Kim 2008).

1.2. Purpose of study

This study explored the integration of augmented reality (AR) and virtual reality (VR) technologies in physics education, evaluating their advantages and challenges in enhancing teaching methods. The research aimed to review analytical literature, assess existing AR and VR applications in education, and propose effective solutions for scientific and pedagogical challenges.

2. METHODS AND MATERIALS

2.1. Research design

This study employed a qualitative research design, incorporating a systematic literature review and an experimental comparison of AR and VR applications in physics education. The research aimed to evaluate the benefits and challenges of AR and VR technologies in enhancing physics instruction, focusing on student engagement, comprehension, and retention.

2.2. Data collection

To assess the impact of AR and VR technologies on student learning outcomes, an experimental study was conducted. In this study, students were divided into two groups:

AR-Based Learning Group – received instructional materials enhanced with AR, allowing interactive visualization of three-dimensional physics concepts.

Traditional Learning Group – used conventional two-dimensional resources such as textbooks and posters.

In the practical component of this research, various activities were conducted to assess the accuracy of predictions made in the introduction and to evaluate the effectiveness of the proposed teaching methodology for solving physics problems using the Augmented Physics constructor. The lessons were structured to include theoretical lectures, which introduced problem-solving concepts, and practical sessions, where students applied these concepts to problem-solving exercises. The curriculum was designed to ensure that subsequent topics built upon previously acquired knowledge. A variety of instructional strategies were employed, including frontal teaching, group work, and game-based learning activities, with a strong emphasis on fostering students' logical reasoning, visual thinking, discussion skills, and creative problem-solving abilities.

To achieve the learning objectives in each lesson, student competency in solving physics problems was assessed through oral inquiries, algorithmic programming, and written exercises using notebook cards. Tasks were assigned based on students' levels of comprehension, including activities such as identifying problem-related diagrams, matching problems to corresponding diagrams and algorithms, and using pre-prepared cards to optimize learning time.

Furthermore, students developed construction reports to document their problem-solving processes. As part of the analytical objectives, peer assessments were conducted, allowing students to review and critically evaluate each other’s work. For synthesis-level learning outcomes, students were tasked with creating structured reports that summarized and synthesized relevant educational material. The analysis of student calculations demonstrated their reliance on the construction-based problem-solving techniques introduced in class.

2.3. Participants

Lessons were implemented for students in grades 7–11 across three schools in the Almaty region, Ile district: KMM #46 Secondary School, KMM #30 Secondary School, and KMM #45 Secondary School. The Augmented Physics program was integrated into physics instruction for students in grades 7–10, following the developed methodology for problem-solving in physics.

2.4. Data analysis

At the evaluation stage, students were encouraged to reflect on the significance of physics concepts and provide supporting evidence beyond what was initially presented. To assess the retention and mastery of material, a final evaluation was conducted in the last lesson.

One of the primary challenges encountered in implementing this methodology was the complexity of high-level physics problems. To address this, special emphasis was placed on teaching students techniques for memorizing and deconstructing complex problems. The integration of augmented reality technology was explored as a means to facilitate the visualization and resolution of construction-based problems.

The experimental phase of the study included a comparative assessment to determine the effectiveness of the augmented reality-based teaching methodology. This assessment was conducted in two phases: (1) before introducing augmented reality, where students attempted to solve physics problems using conventional methods, and (2) after the implementation of augmented reality-based instruction. The pre-study assessment aimed to identify students' initial problem-solving strategies, while post-study observations were conducted through written evaluations to analyze the methods used by students after exposure to the new instructional approach.

Key metrics, including engagement levels, comprehension rates, and attention span, were compared between the groups. The results indicated that AR-based learning significantly improved student participation and knowledge retention compared to traditional methods.

3. RESULTS

3.1. Control work tasks

The control results for each student's performance in solving these problems are presented in Table 1. The steps followed are seen below:

- Magnetic Induction and Motion on an Inclined Plane
  Determine the maximum velocity of a body with mass mmm and charge qqq moving along an inclined plane under the influence of both a magnetic field and a gravitational field.
- Thermodynamics of Moving Pistons
  Consider a system with pistons of mass mmm. At the initial moment, the pistons move in the same direction with velocities 3ϑ3\vartheta3ϑ and ϑ\varthetaϑ, respectively. Determine the maximum temperature to which the gas in the system heats up.
- Sound Propagation in Water
  A person underwater perceives a sound originating from a source located 14.72 meters above the water surface after a time interval of 50 milliseconds. Determine the relevant physical parameters governing the sound's propagation.

Table 1

The students created these reports using the Augmented Reality-based teaching method before beginning their studies.

I	Student name	1 - question	2- question	General	Percentage
1	Student 1	5	5	10	100
2	Student 2	4	5	9	90
3	Student 3	5	5	10	100
4	Student 4	4	4	8	80
5	Student 5	5	4	9	90
				Average percentage	48

After participating in the lesson, when checking observational work, almost all students noted that they solved problems in physics at a high level and understood them very well. However, some have made the report wrong. The results can be seen in the following table 2.

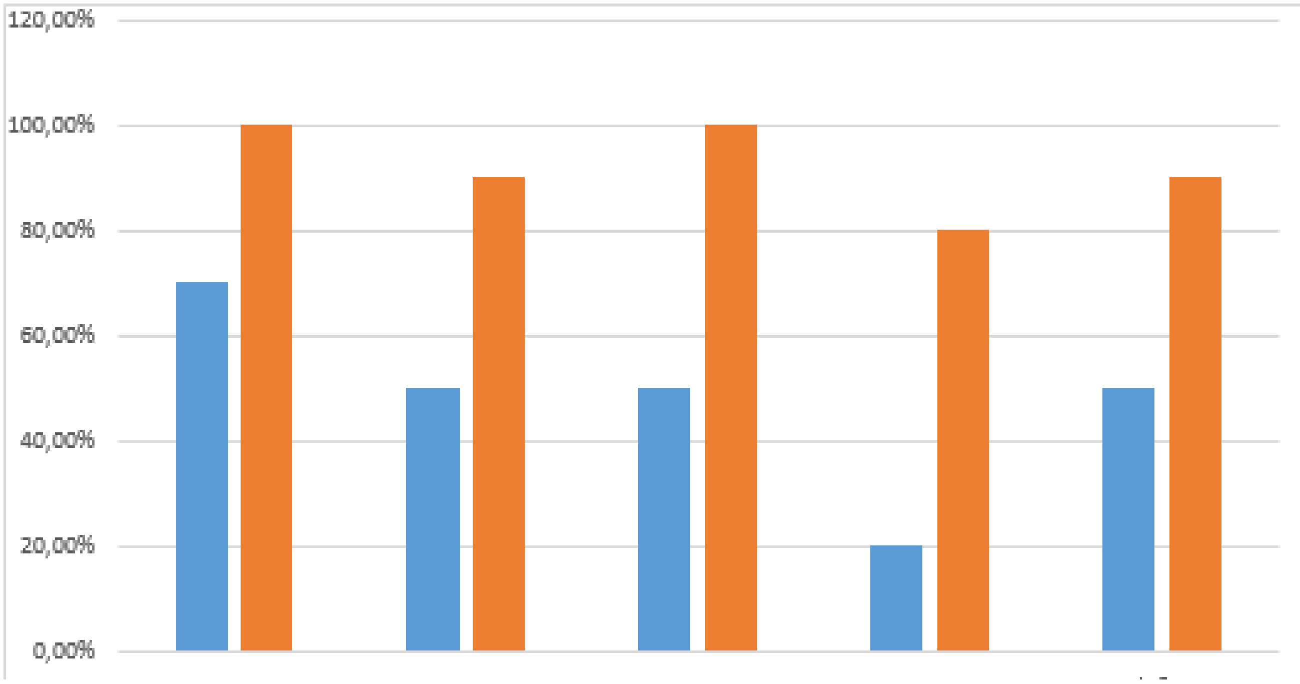
Table 2

The results of the students' control work on construction tasks, generated using the "Augmented Physics" constructor.

I	Student name	1 - question	2- question	General	Percentage
1	Student 1	5	5	10	100
2	Student 2	4	5	9	90
3	Student 3	5	5	10	100
4	Student 4	4	4	8	80
5	Student 5	5	4	9	90
				Total	92

Figure 1

Results of the students' post-study control work on the construction problems created using the Augmented Physics constructor.



Note: Blue represents before using augmented reality

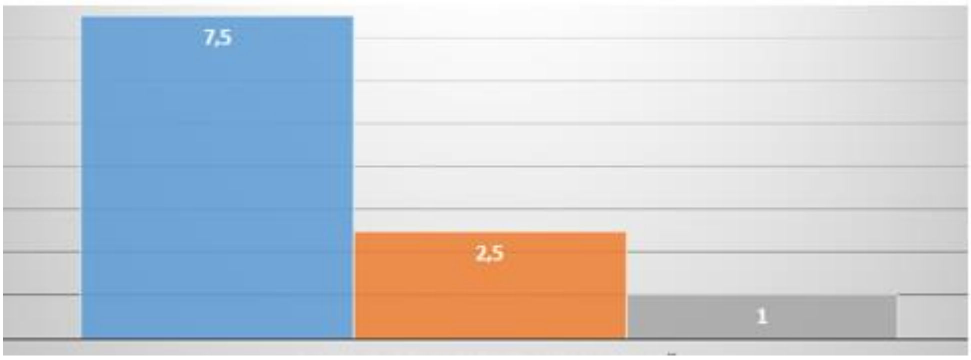
After participating in the lesson and during the observation inspection, nearly all students reported that they were able to solve physics problems at a high level and had a strong understanding of the concepts. However, some students made errors in their reports. The results are presented in Table 2.

As shown in Figure 1, the test papers in the appendix provide insight into the methods each student used to solve problems before and after studying according to the developed methodology.

Several main advantages of implementing AR technologies in education have been identified; Figure 2 summarizes the results.

Figure 2

Diagram of the results of comparison of types of physical education



Notes:

Blue - augmented reality

Yellow - online learning

Gray - traditional training

4. DISCUSSION

The observed differences in results before and after the implementation of the prepared methodology cannot solely be attributed to whether students participated in the lesson or not. Several factors likely influenced the outcomes, including students' prior knowledge, their abilities in logical and visual spatial thinking, their general academic progress, their proficiency in mathematics, and their mental state during the observation and writing of reports. Additional variables, such as the students' lack of preparation before the first control and the time lapse before the second control (which may have led to forgetting construction techniques), could have played a role. Thus, as the results indicate, the ability to make informed judgments during geometric construction problem solving is more crucial than merely knowing the methodology.

In light of these findings and based on research conducted by other scholars, a group of authors developed an augmented reality application in 2021 that highlights the practical benefits of the educational process in both traditional school subjects and extracurricular learning. The primary aim of this application was to encourage a conscious interest in learning outside the classroom. To achieve this, students were introduced to their classroom environment, where they could explore additional educational programs. Not only could they visualize the projects created in the class, but they could also understand the interdisciplinary connections and the technologies used in these activities.

For students using this application, the method of presenting material proved more effective than traditional field trips, as demonstrated in an experiment with students from grades 7 to 11. The experiment aimed to increase students' conscious engagement with learning through this innovative tool. Students who were unfamiliar with the Center for Innovative Creativity of Youth at the school were first presented with traditional photographs of the classroom. Subsequently, they were shown the AR application, allowing them to explore the virtual classroom, interact with objects, and access audiovisual content.

The results of the experiment revealed significant differences between the two methods of learning. When students learned through photographs, their interest in the class and project activities was minimal. However, using the AR application significantly increased their engagement, as students felt more immersed in the environment and were able to interact with the educational content more dynamically. The awareness of the material presented increased from 45 percent with traditional methods to 80 percent when using AR, and the attention paid to the learning process rose from 60 percent to 97 percent.

As shown in Figure 2, students who spent more time touring the virtual classroom demonstrated a higher level of engagement and motivation to learn. This reinforces the importance of developing such tools for educators. According to the results of this experiment, augmented reality has a positive impact on motivating conscious learning and can significantly enhance the educational process.

Building on these findings, the team of authors began developing an AR application specifically designed for history classes and historical tours in Almaty. This app will allow students to explore the city as it appeared in the 1870s, including virtual depictions of buildings, streets, and historically significant figures. The application's interactive elements further enhance immersion and student involvement. Surveys conducted with younger students indicated that experiencing living history through AR greatly increased their interest in studying local history.

These examples underscore the potential of AR as a vital tool for educators—not only to teach theory and provide practical experience but also to stimulate students' awareness and engagement with learning. Interactive teaching methods, such as AR, enable a deeper understanding of the learning material by focusing on students' motivation. This is especially important for younger students, as fostering a conscious approach to learning increases their motivation and sets the foundation for continued academic engagement in the future.

In subjects like biology, chemistry, physics, and mathematics, the development of AR tools such as three-dimensional laboratories and interactive textbooks can dramatically improve the quality of education. These technologies make learning more engaging and help students achieve a higher level of awareness and understanding. The advantages of AR in education are clear: traditional methods are often costly and less effective, while the development of AR applications has become increasingly accessible for mass use, making it a practical and efficient educational tool (Johnson and Johnson, 1986).

Augmented reality (AR) and virtual reality (VR) technologies offer significant advantages in various fields of education and professional training. First, visibility is one of the key benefits of these technologies. With 3D graphics, it is possible to reproduce in intricate detail processes that are invisible to the human eye, such as chemical reactions, atomic nucleus decay, electron movement, and cellular development at different stages. This enables learners to observe and understand complex scientific phenomena that would otherwise be difficult to conceptualize.

Safety is another critical area where VR and AR play an essential role, particularly in fields that involve high-risk activities. For example, training programs for pilots, medical operations, and technical equipment usage in hazardous industries benefit from virtual simulations, where learners can practice skills without exposing themselves to danger. The creation of virtual environments, such as cockpit simulations, illustrates the advantages of these technologies in allowing individuals to experience high-risk situations safely.

Additionally, new opportunities for distance learning have emerged with the advancement of VR and AR technologies. These tools allow the creation of immersive, simulated environments that can bring new life to subjects such as history. Students can experience historical events from a first-person perspective, enhancing their understanding and engagement. By stepping into virtual worlds, students can actively participate in the events they are studying, which is a more dynamic learning experience compared to traditional methods.

The agreement that these technologies offer in terms of visualization is undeniable. The mechanics of complex systems, such as the human body, can be visualized in ways that traditional teaching methods cannot match. VR and AR technologies allow students to “travel through time” or explore distant parts of the universe, providing immersive learning experiences that go beyond the scope of textbooks. This enhanced visualization helps students grasp difficult concepts by interacting with the material rather than merely reading about it.

Concentration is another advantage that VR and AR technologies bring to education. Immersion in a detailed virtual environment minimizes distractions from external factors, allowing learners to focus more intently on the subject matter. This full immersion is particularly beneficial for educational activities where concentration is essential for learning complex concepts. Furthermore, mixed-reality tools, which blend real and virtual elements, help eliminate distractions from the surrounding environment. For example, in the transportation sector, companies have developed specialized apps for engineers and mechanics that integrate AR and VR technologies. These applications, which can be used with tablets, smartphones, or AR glasses, allow professionals to access real-time information while working, improving both safety and efficiency (Sumadio & Rambli, 2010).

A similar project was developed at the University of Iowa, where engineers created a virtual cockpit for advanced driving simulators. This cockpit, equipped with sensors that track a driver’s actions, provides a 360-degree view of the driving environment and simulates real-world road conditions. The system has been used to study various aspects of road safety and driver behavior (Wagner et al., 2006). Additionally, VR technology is also employed to study pedestrian and cyclist behavior in virtual environments. Simulating scenarios where children or cyclists cross busy roads helps to identify potential risks and improve safety measures (Campos et al., 2011).

In large-scale urban planning, virtual simulations are being used to optimize transportation systems. For example, students, in collaboration with city residents, are working on a project to create a “virtual Singapore” using drones, 3D visualization software, and VR. This project simulates real-life urban dynamics, such as traffic flow and parking needs, helping urban planners make informed decisions about infrastructure development and traffic management (Li et al., 2011).

One prominent example of VR technology in infrastructure planning is the CrossrailVR system developed by British engineers for the construction of the Underground Railroad. Using advanced tools like drones, laser scanners, and photogrammetry, this system creates 360-degree virtual projections of construction sites, allowing engineers and designers to explore the site in real time. The system integrates building information modeling (BIM) to ensure accurate data management and design verification, ultimately improving collaboration and project efficiency (Boletsis & McCallum, 2013).

Finally, VR technologies allow for the visualization of complex service systems in infrastructure projects, such as intricate networks of pipes and cables. This visualization helps engineers avoid potential issues during construction and ensures the safety and efficiency of the building process. The ability to see and interact with these systems in a virtual environment ensures that all components are correctly planned and coordinated (Dede, 2009).

5. CONCLUSION

New technologies are deeply embedded in our lives and change our attitude towards education. But at the same time, it should be understood that the proposed game world should be compatible, coherent, and whole with the real world. All actions and decisions of students of grades 7-10 should be consistent, feedback, and focus. For the listeners to clearly understand the purpose and practical importance of the training, it is necessary to understand the meaning of the game. The main task of the games is to interest students in the subject, motivate them, and develop their desire to learn new things.

The integration of games into the learning process is increasingly used as an effective teaching method, especially by teachers of additional education and universities. At the same time, traditional methods such as "handwriting" or oral counting should not be abandoned, they should complement each other because AR tools allow us to convey the main thing - the semantic component of education. Due to the great didactic potential of educational computer games, it is possible to be sure that in the future, effective technology for the educational process will be developed that fully meets the requirements of the educational community today. The purpose of the work is to analyze the known methods of using augmented and virtual reality. The most promising solution to various scientific problems is the maximum use of virtual reality in school programs. We achieved this goal during the experiment conducted in three schools.

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