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B.S. Arymbekov[1*], K.M. Turekhanova[1], K. Fedus[2], N. Suprapto[3], E.R. Tursanova[4] M. Turdalyuly[4]

[1]Al-Farabi Kazakh National University, Kazakhstan, Almaty
[2] Nicolaus Copernicus University, Poland, Toruń
[3]Surabaya State University, Indonesia, Surabaya
[4]Kazakh National Research Technical University named after K.I. Satpayev, Kazakhstan, Almaty
*e-mail: beckemn@mail.ru

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

The article provides a comprehensive exploration of the utilization of augmented reality technologies in the field of education, with a particular focus on physics education. The primary objective of this study is to identify and examine the advantages and disadvantages of existing and previously developed teaching methodologies in physics that incorporate augmented reality, particularly in the context of their educational effectiveness. The article underscores the ability of AR to enable direct interaction with three-dimensional models and objects, allowing users to examine them from various angles and access relevant information. This capability enhances the understanding of complex physics concepts and phenomena. The article emphasizes the significance of adequately training teachers in the integration of augmented reality technology into the teaching process. Teachers need to be proficient in using AR tools and incorporating them into the curriculum effectively. The article highlights the potential for students to engage in project-based activities by creating their own AR applications. This participatory approach fosters active learning and experimentation. The article explores different pedagogical approaches and methods for teaching physics using augmented and virtual reality technologies. These innovative methods enrich the educational experience and make it more interactive. This article underscores the importance of augmented reality technologies in education. The practical part of the study involved 750 students from schools in Kazakhstan. The research results were processed using statistical methods.

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

Б.С. Арымбеков[1,*], К.М. Турееханова[1], К. Федус[2],
Н. Супрапто[3], Э.Р. Турсанова[4], М. Турдалыулы[4]

[1]Әл-Фараби атындағы Қазақ ұлттық университеті, Қазақстан, Алматы қ.
[2]Николай Коперник Университеті, Польша, Торун қ.
[3]Сурабай мемлекеттік университеті, Индонезия, Сурабай қ.
[2]Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті, Қазақстан, Алматы қ.
*e-mail: beckemn@mail.ru

Орта мектепте физика пәнін оқыту мақсатында GeoGebra бағдарламасымен толықтырылған шынайылықты тұтынудың әсері

Мақалада физика біліміне ерекше назар аудара отырып, білім беру саласында толықтырылған шындық технологияларын қолдану жан-жақты қарастырылған. Бұл зерттеудің негізгі мақсаты – толықтырылған шындықты қамтитын физикадағы қолданыстағы және бұрын жасалған оқыту әдістемелерінің, әсіресе олардың білім беру тиімділігі контекстінде артықшылықтары мен кемшіліктерін анықтау және зерттеу. Мақалада AR-ның үш өлшемді модельдермен және нысандармен тікелей өзара әрекеттесу мүмкіндігіне баса назар аударылады, бұл пайдаланушыларға оларды әртүрлі бұрыштардан тексеруге және тиісті ақпаратқа қол жеткізуге мүмкіндік береді. Бұл мүмкіндік күрделі физика ұғымдары мен құбылыстарын түсінуді жақсартады. Мақалада толықтырылған шындық технологиясын оқыту үдерісіне кіріктіруде мұғалімдерді барабар дайындаудың маңыздылығы атап өтілген. Мұғалімдер AR құралдарын қолдануда және оларды оқу бағдарламасына тиімді енгізуде шебер болуы керек. Мақалада студенттердің жеке AR қосымшаларын жасау арқылы жобаға негізделген әрекеттерге қатысу мүмкіндігі көрсетілген. Бұл қатысу тәсілі белсенді оқыту мен эксперимент жасауға ықпал етеді.

Мақалада кеңейтілген және виртуалды шындық технологияларын қолдану арқылы физиканы оқытудың әртүрлі педагогикалық тәсілдері мен әдістері қарастырылған. Бұл инновациялық әдістер білім беру тәжірибесін байытады және оны интерактивті етеді. Бұл мақала білім берудегі толықтырылған шындық технологияларының маңыздылығын көрсетеді. Зерттеудің тәжірибесіне Қазақстан мектептерінен 750 оқушы қатысты. Зерттеу нәтижелері статистикалық әдістермен өңделді.

Түйін сөздер: физиканы оқыту, оқыту әдістемесі, орта білім, толықтырылған шынайылық, физиканы оқытуға арналған қосымшалар.

Б.С. Арымбеков[1,*], К.М. Туреханова[1], К. Федус[2],
Н. Супрапто[3], Э.Р. Турсанова[4], М. Тұрдалыұлы[4]

[1]Казахский национальный университет имени аль-Фараби, Казахстан, г. Алматы
[2]Университет Николая Коперника, Польша, г. Торун
[3]Государственный университет Сурабая, Индонезия, г. Сурабай
[4]Казахский национальный исследовательский технический университет имени К.И. Сатпаева, Казахстан, г. Алматы
*e-mail: beckemn@mail.ru

Эффект применения программного обеспечения Geogebra для визуализации дополненной реальности для преподавания физики в средних школах

В статье представлено исследование использования технологий дополненной реальности в сфере образования, в частности на уроках физики. Основная цель исследования – выявить преимущества и недостатки существующих и ранее разработанных методик обучения физике, включающих дополненную реальность, в том числе в контексте их образовательной эффективности. В статье подчеркивается способность AR обеспечивать прямое взаимодействие с трехмерными моделями и объектами, позволяя пользователям рассматривать их под разными углами и получать доступ к соответствующей информации. Эта возможность улучшает понимание сложных физических концепций и явлений. В статье подчеркивается значимость подготовки учителей по интеграции технологий дополненной реальности в учебный процесс. Учителя должны владеть навыками использования инструментов AR и эффективно включать их в учебную программу. В статье освещаются возможности участия учеников в проектной деятельности путем создания собственных AR-приложений. Такой подход, основанный на участии, способствует активному обучению и экспериментированию. В статье исследуются различные педагогические подходы и методы преподавания физики с использованием технологий дополненной и виртуальной реальности. Эти инновационные методы обогащают образовательный опыт и делают его более интерактивным. В практической части исследования приняли учатие 750 учеников школ Казахстана. Результаты исследования были обработаны статистическими методами.

Ключевые слова: обучение физике, методика преподавания, среднее образование, дополненная реальность, приложения по обучению физике.

Introduction

The present research aims to investigate the impact of augmented reality technology on physics teaching in setting at the high school level. The focus is on comparing the educational outcomes of virtual reality and augmented reality designs (Ozdamli, et al., 2017:121). This research is motivated by the increasing interest in integrating augmented reality into educational settings due to its potential to visualize complex 3D phenomena and enhance pupil engagement. Physics teaching at the high school level often involves personalized interactions between pupils and instructors, such as during office hours or private tutoring sessions, which can occur in person or remotely through online video conferencing (Kaur, et al., 2020:881) . While previous studies have shown the benefits of augmented reality for physics education when pupils independently interact with augmented reality content, there is a lack of research on its specific application in physics teaching settings. Additionally, little is known about how the complexity of an augmented reality experience affects pupil learning. (Chen, et al., 2020:1052) . The hypothesis is that increasing the complexity of an augmented reality application can lead to stronger educational. Complexity refers to factors such as the ability of the application to track real objects and anchor visualizations to moving objects, the use of dynamic and 3D visualizations instead of static and 2D ones, and the quantity of augmented reality visualizations (Moro, et al., 2021:680) . However, developing complex augmented reality applications is costly, which can be a barrier to widespread adoption and usage. Therefore, it is important to study how design decisions in augmented reality application development affects learning outcomes (Chou, et al., 2021:383) . The research scenario involves an instructor wearing an augmented reality headset to view visualizations overlaid on real objects while teaching physics concepts. The pupil, on the other hand, remotely views the instructor's perspective through a computer screen (Chang, et al., 2020:7854) . This setup allows both the instructor and pupil to have the same perspective on the learning activity. The instructor can manipulate physical objects using their hands, and the pupil can view the augmented reality visualizations on the computer screen without needing their own augmented reality device (Demitriadou, et al., 2020:381) . The goal is to create an augmented reality-enhanced physics-teaching scenario that addresses various limitations and is accessible to educators without requiring specialized knowledge of augmented reality technology (Zhang, et al., 2020:4) . The chosen context of high school physics teaching is valuable for research because not only it allows for understanding how augmented reality can benefit existing physics teaching situations, but also because it provides methodological advantages in studying pupil thought processes (Huang, et al., 2021:927) . While augmented reality has shown potential in improving learning gains, reducing cognitive load, enhancing performance time, and promoting collaboration, the mechanisms through which augmented reality visualizations generate these outcomes are not fully understood (Chin, et al., 2021:27) . The interaction between pupils and instructors in the context of high school physics teaching can shed light on the mechanisms by which augmented reality visualizations influence learning processes (Buchner, 2021:701) . Unlike situations where pupils interact with augmented reality experiences directly without speaking, collaborations such as high school physics teaching allow for verbal interactions and pupil questioning, providing additional information on how augmented reality visualizations influence pupils (Arymbekov, et al., 2020a:57) . Pupil dialogues can reveal what pupils are paying attention to, identify topics that challenge their understanding, and capture their thought processes at different stages of the activity. These insights into learning processes through high school physics teaching interactions can provide a deeper understanding of how different aspects of the augmented reality experience influence pupil learning behaviors, complementing the existing knowledge on the general benefits of augmented reality (Cai, et al., 2021:235) . The chosen augmented reality physics teaching situation meets the established criteria of augmented reality, as it combines real and virtual content (overlaid visualizations on real-world objects), enables interactivity, and is registered in 3D (Garzón, et al., 2020:69) . This remote augmented reality experience resembles other applications of augmented reality, such as when an expert guides a remote worker or a collaborator guides a remote tactical team member. In this context, pupils can observe the impact of instructor actions in augmented reality through the computer screen and engage in active learning strategies by asking questions, making requests, and receiving feedback from the instructor (Thees, et al., 2020:1050). Through the use of a novel augmented reality system and a controlled study, this research aims to explore the effects of augmented reality technology on pupil learning gains, as well as their inquiry and communication with the instructor (Eldokhny, et al., 2021:198) . The integration of augmented reality involves teaching scientific concepts through external representations while supporting active inquiry and encouraging social interactions. To provide a comprehensive understanding, the study first reviews the relevant literature on these subtopics before presenting the research questions and study design (Arymbekov, 2020б:19) .

Related works

Previous research in the literature has demonstrated the positive impact of augmented reality on pupil learning outcomes in physics education (Guntur, et al., 2021:159) . However, there is a scarcity of studies that specifically investigate the interactions between pupils and instructors in augmented reality enabled high school knowledge exchange (Marini, et al., 2022:99) . This research aims to address this gap by focusing on the unique context of augmented reality enhanced physics teaching between pupils and instructors (Hsieh, 2021:2818) . Comparative studies in augmented reality learning often compare augmented reality experiences to traditional paper-and-pen or computer-based learning methods (Sahin, et al., 2020:155) . However, such approaches may not adequately control for the effects of novelty and differences in information representation between augmented reality and traditional methods (Lee, et al., 2021:6434) . For instance, the use of cuttingedge augmented reality technology can increase pupil motivation and engagement, while the interactive nature of augmented reality visualizations allows for greater agency and experimentation compared to non-interactive textbooks (Christopoulos, et al., 2021:307) . Additionally, the sequence of concept presentation may differ between augmented reality and textbooks. (Suhaizal, et al., 2023:162) . While such studies can highlight the potential of augmented reality technology for improving educational outcomes, they may struggle to identify the specific variables influencing pupil learning. To address these limitations, the present study aims to minimize the differences between experimental conditions to better understand how the augmented reality application influences pupil learning (Wahyu, et al., 2020:343) . Both experimental conditions in this study utilize augmented reality technology to control for the effects of novelty. Furthermore, both conditions allow pupils agency to ask questions and receive feedback. A similar instructional sequence is followed to ensure that pupils are exposed to the same concepts in the same progression. Previous research has proposed taxonomies to guide the design of augmented reality applications (Alqarni, 2021:558). These taxonomies identify design dimensions that can benefit learning outcomes at the expense of increased complexity in augmented reality applications. Examples of design dimensions include the reference system (anchoring augmented reality content to the real world or not) and visual connection (anchoring augmented reality visualizations spatially to objects or using other mechanics such as virtual lines) (Mukhtarkyzy, et al., 2020:201). By considering these taxonomies and evaluating the impact of different design dimensions, this research aims to contribute to the understanding of how augmented reality application design choices can influence pupil-learning outcomes in physics education. In the context of augmented reality applications for physics education, the complexity of the visualizations and the types of representations used can have an impact on pupil learning and inquiry processes. Spatially anchoring virtual content to objects in the augmented reality application can enhance understanding for users, but it requires more complex software development for object tracking (Arymbekov, et al., 2023:125) . The present research aims to extend existing work by comparing augmented reality augmented reality application (involving multiple dynamically changing 3D visualizations anchored and moving with real objects) to a virtual reality version. The goal is to investigate how these design differences influence pupil learning and inquiry processes, particularly in understanding complex physics phenomena. Understanding complex phenomena in physics requires pupils to comprehend multiple scientific sub concepts and their relationships (Nurbekova, 2020:212). The theories of social constructivism and distributed cognition suggest that pupils develop such complex understanding through interactions with others and artifacts. (Elmira, et al., 2022:33). Thus, pupils gain knowledge not only from the tutor but also through interactions with the instructor and the information representations in the learning activity. Research on animated digital representations and knowledge construction has shown that the process of making conceptual links is supported by collaborative sense-making through interaction with others and with the animations visible on the computer screen. The specific ways in which information is represented in the learning environment can aid this process. Multiple representations, such as different scientific concepts displayed for a simulated body (e.g., mass, force, friction, velocity), can help pupils develop relational understanding, reduce cognitive load, facilitate deeper understanding, and support knowledge transfer to new situations. In augmented reality systems, multiple interactive representations can allow pupils to recalibrate their understanding of complex concepts and construct deeper understanding of phenomena by observing the dynamic linking of individual representations (Eldokhny, et al., 2021:198) . By exploring these aspects, the present research aims to shed light on the impact of augmented reality application complexity and design choices on pupil learning and inquiry processes in physics education. In our study, we aim to investigate how augmented reality visual representations influence pupil understanding of scientific concepts and their inquiry processes through communication with the instructor (Arymbekov, 2023в:52) . Pupil inquiry is crucial for knowledge development and is an important topic of research in collaborative learning environments with AR. From a social-cognitive perspective, conceptual change in scientific thinking emerges from pupils' inquiry process and their approach to asking questions. Previous research has shown that pupil-generated questions can lead to productive discussions and meaningful knowledge construction (Afnan, et al., 2021в:5277) . Asking questions allows pupils to check their understanding, fill knowledge gaps, monitor and self-evaluate their learning, and adjust their learning strategies. Pupil inquiries can also reveal conceptual difficulties and drive pupils to search for patterns, connect with prior knowledge, and build bridges to new understanding. It has been observed that less knowledgeable pupils tend to ask more basic questions, while more knowledgeable pupils ask higher-level questions. To analyze and quantify different types of pupil inquiries and understand how they connect to thinking strategies, a qualitative coding scheme has been developed (Weng, et al., 2020:747). This scheme classifies different types of questions and inquiries, ranging from basic information gathering to experimentation/exploration and hypothesis generation/reflection. Additionally, it has been found that pupils who persevere and continue to ask questions from multiple perspectives are able to redirect their efforts and eventually arrive at meaningful insights (Arymbekov, 2023г:128). Pupils who engage in different types of inquiry styles tend to demonstrate better learning outcomes (Sugandi, et al., 2022:199) . Moreover, if pupil questions receive appropriate answers that guide them to proceed with the next steps of the inquiry, they are more likely to remain motivated and actively involved in the activity. In our study, we plan to expand on the qualitative model developed previously and apply it to investigate how augmented reality content influences pupil inquiry styles (Arymbekov, et al., 2023д:157). By examining the types of questions and inquiries generated by pupils in the context of augmented reality, we seek to understand how the augmented reality visual representations impact their inquiry processes (Saitnabieva, et al., 2023:17) . This research will provide valuable insights into the relationship between augmented reality design and pupil inquiry, contributing to a deeper understanding of how augmented reality can enhance learning experiences in physics education (Baurzhan, et al., 2022:96). In the field of augmented reality for education, research has demonstrated that augmented reality visualizations, also referred to as augmented reality visual representations, play a significant role in guiding pupil inquiry and fostering active collaboration, thereby improving problem-solving approaches among peers. Collaborative activities using augmented reality visualizations have shown positive outcomes in teaching and learning (Aviandari, et al., 2023:41).

Methodology

In collaboration with physics domain experts, the researchers have developed an augmented reality system specifically designed for teaching Faraday's Law, which are electromagnetism concepts related to the interaction between a moving magnet and electrical field of wire. These laws explain how the changing magnetic electromagnetic waves induced by the magnet's movement can generate an electric current and an opposing magnetic force in the electrical field.

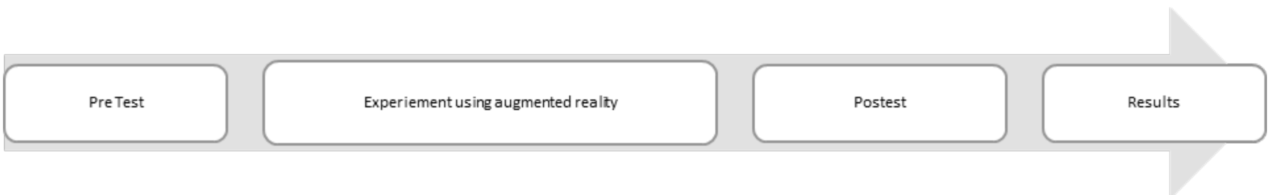

Figure 1 – Experimental study process of physics laboratory.

Traditionally, pupils learn these concepts through formulas and figures in textbooks or by conducting experiments with physical objects, such as measuring voltage near a electrical field of wire. However, the researchers have introduced an augmented reality system to enhance the learning experience. In this system, the instructor wears headset and utilizes dynamic 3D augmented reality visualizations that are overlaid onto a physical magnet and electrical field.

The augmented reality system allows the instructor to provide a more immersive and interactive learning experience for the pupils. By visualizing the concepts in 3D and overlaying them onto physical objects, the system aims to enhance the pupils' understanding of Faraday's Law and Lenz's Law (Fig.1). The augmented reality visualizations can help pupils observe and comprehend the relationship between the magnet's movement, changing magnetic electromagnetic waves, induced current, and opposing magnetic force.

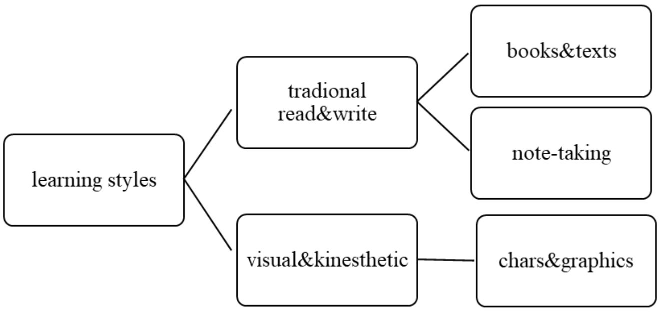

Figure 2 – Research design and implementation. Procedures

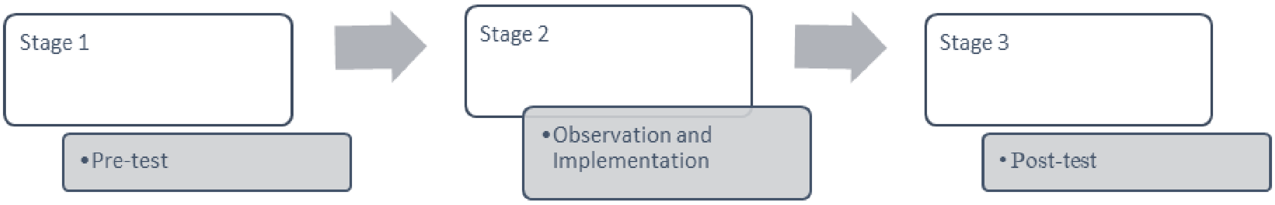

Figure 3 – Research design and implementation. Procedures of experiment

The use of augmented reality in this context provides an alternative and potentially more engaging approach to teaching these complex concepts. By incorporating augmented reality technology, the researchers aim to bridge the gap between theoretical understanding and real-world applications, providing pupils with a more tangible and interactive learning experience. The teaching sequence for explaining Faraday's Law and Lenz's Law using augmented reality is structured into three parts, following a typical physics teaching session at the high school level. In the first part, the instructor introduces the physical objects, namely the magnet and the electrical field, and asks the pupil to make a prediction about what would happen if the magnet is moved towards the electrical field. The instructor then proceeds to teach and demonstrate the sequence of events described earlier while encouraging the pupil to interrupt with questions at any time.

The augmented reality visualizations, such as the yellow arrow visualization representing the induced current in the electrical field and the simplified graph visualization depicting the strength of the magnetic electromagnetic waves, dynamically change with the movement of the magnet to show the interrelation between multiple physics concepts. The instructor concludes this part by prompting the pupil to ask any remaining questions they may have. In the second part, the instructor covers the scenario in which the magnet is moved away from the electrical field. This scenario results in physical behaviors opposite to those observed in the first scenario and aims to solidify the pupil's understanding of the concepts.

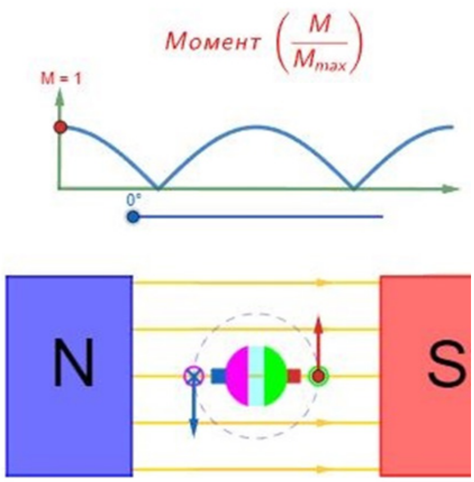

Figure 4 – Traditional visualizations of condition of Faraday's Law.

The same augmented reality visualizations used in the first part are employed, and the instructional structure remains the same, including a prediction question, instructional material, and a prompt for further questions. In the third part, the instructor focuses on the scenario where the electrical field is moved towards the stationary magnet. This scenario is similar to the first scenario, but the concept of induced forces becomes more prominent.

Figure 5 – Experimental scene
to visualize condition of Faraday's Law.

Figure 6 – Preparation of visualizations
of condition of Faraday's Law.

The instructional approach follows the same structure as in the previous parts, with prediction questions, instructional material, and a prompt for questions. At the conclusion of the three parts, the instructor asks the pupil if they have any additional questions that may be relevant to their coursework, allowing for further clarification or discussion.

By utilizing augmented reality and interactive visualizations, this instructional approach aims to engage pupils in the learning process and provide a deeper understanding of the complex concepts associated with Faraday's Law and Lenz's Law (Fig.2).

Figure 7 – Physics lab scene with AR for visualizations
of condition of Faraday's Law.

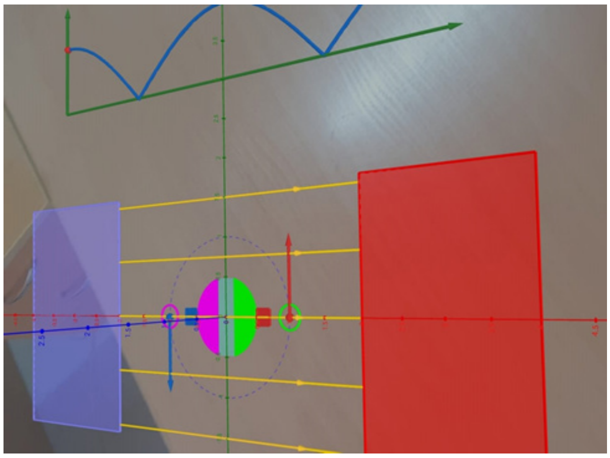

Figure 8 – Augmented reality visualizations condition
of Faraday's Law.

In this study, two conditions were implemented to compare the influence of augmented reality content complexity on pupil learning and inquiry. The experimental condition, referred to as "Augmented reality," involved a high degree of augmented reality complexity. In this condition, the instructor utilized the dynamic 3D visualizations described earlier, which included multiple visualizations that were anchored and moving with the real objects. These visualizations provided a rich and interactive augmented reality experience. On the other hand, the control condition, referred to as "Traditional study," involved a low degree of augmented reality complexity. In this condition, the instructor used basic visualizations, such as a static representation of magnetic field lines that did not follow the movement of the magnet, and a simplified up/down arrow to indicate the direction of electricity. These visualizations were 2D and did not dynamically change with the movement of the objects. Both conditions included some degree of augmented reality visualizations and were viewed from the same instructor perspective, ensuring that the differences between the conditions were primarily related to the complexity of the augmented reality content. This design choice aimed to control for potential differences in pupil excitement or novelty associated with augmented reality technology. Additionally, it ensured that both conditions maintained a similarity in terms of pupils observing the instructor's physical environment. Both conditions followed the 3-part instructional sequence outlined earlier and maintained similarities in the instructor's personality and instructional style. This further ensured consistency across conditions, except for the differing complexity of the augmented reality content. By comparing these two conditions, the researchers aimed to investigate how the complexity of augmented reality content influenced pupil learning and inquiry in the context of physics teaching. To assess the impact of augmented reality content complexity on pupil learning and inquiry, the researchers collected and analyzed data related to participants' learning gains, inquiry styles, and references to augmented reality visualizations and scientific concepts.

Table 1– The list of criteria to collect data to analyze

Learning indicators	Effects of the augmented reality
Learning Gains	The researchers measured participants' learning gains by comparing their pre-test and post-test scores on physics-related knowledge and concepts. The pre-test was administered before the instructional sequence, and the post-test was conducted after the completion of the sequence. The scores from both tests were analyzed to determine the extent of learning that occurred during the instructional intervention.
Inquiry Styles	The researchers employed a coding scheme to analyze participants' inquiry styles during the instructional sequence. The coding scheme was designed to identify different inquiry styles, such as structured inquiry, guided inquiry, and open inquiry. Observational data, including video recordings or written transcripts, were used to identify and categorize the inquiry styles exhibited by the participants.
References to augmented reality	The researchers also collected data on participants' references to augmented reality visualizations and scientific concepts during the instructional sequence. This data was obtained through qualitative analysis of the participants' verbal interactions, questions, and discussions with the instructor.
Visualization Concepts	The researchers noted instances where participants made specific references to augmented reality visualizations and connected them to relevant scientific concepts.

The collected data was then analyzed using both quantitative and qualitative methods. Quantitative analysis involved statistical techniques to assess the differences in learning gains between the Augmented reality and Traditional study conditions. Qualitative analysis focused on thematic analysis of the inquiry styles and the references made to augmented reality visualizations and scientific concepts. This allowed the researchers to identify patterns, themes, and relationships within the data. The combination of quantitative and qualitative analysis provided a comprehensive understanding of how the complexity of augmented reality content influenced pupil learning outcomes, inquiry styles, and the integration of augmented reality visualizations with scientific concepts. To assess learning outcomes, a pre-test and post-test were administered to measure pupils' understanding of physics concepts related to Faraday's Law and Lenz's Law. The test questions were developed in collaboration with two physics domain experts who have experience teaching and assessing pupils on the same content. These questions presented scenarios that involved the relationships between magnet movement, electric current, and physical forces. The test also included transfer questions, which aimed to assess pupils' ability to apply their knowledge to situations beyond what was covered in the instructional activity. These transfer questions challenged pupils to demonstrate their understanding of the concepts in novel contexts. To calculate learning metrics, relative learning gains were employed. Relative learning gains account for the fact that it may be difficult to score all the test points and that a participant's score may not increase as much if they already have a high pre-test score. The relative learning gain is calculated as the ratio between the actual improvement in scores (post-test score minus pre-test score) and the total amount of possible improvement (max achievable score minus pre-test score). The relative learning gains were computed for various learning metrics, including overall learning score, ability to transfer knowledge, and conceptual understanding of induced magnetic field, electrical field current, and physical forces. Statistical analysis was conducted to determine if there were significant differences between the augmented reality and Traditional study conditions. For parametric assumptions, such as normal distribution, T-tests were used. Non-parametric Wilcoxon-Mann-Whitney tests were employed when the assumptions were not met. Both conditions ensured equal opportunities for pupil engagement. Pupils were informed at the beginning that they could interrupt and ask questions at any time during the instructional sequence. Additionally, at the end of the three instructional sections, the instructor explicitly asked pupils if they had any questions. By analyzing the learning test results and applying appropriate statistical tests, the researchers aimed to determine the impact of augmented reality content complexity on pupils' learning outcomes. Participants for this study were recruited from physics classes at high school in Kazakhstan. The inclusion criteria required participants to be adults currently enrolled in an introductory physics course that covered the topics of Faraday's Law and Lenz's Law. Participants were required to have attended at least one class lecture introducing these laws. Participation in the study was voluntary and did not count for course credit. The study took place outside of regular course periods. All participants provided voluntary consent to participate in the study, and the research protocol was approved by the university's institutional ethics review board. A total of 750 pupils participated in the study and were randomly assigned to one of the two conditions, with 35 pupils in each condition. The average age of the participants in the full sample was 16.5 years, with a standard deviation of 5.3. The age range was between 19 and 35 years. Regarding gender distribution, there were 177 female participants, 571 male participants, 2 nonbinary participants, and 1 participant who did not disclose their gender. In the Augmented reality condition, the average age was 17.4 years, with a standard deviation of 5.5. The age range in this condition was between 16 and 19 years. There were 215 female participants, 146 male participants, and 1 nonbinary participant. In the Traditional study condition, the average age was 17.6 years, with a standard deviation of 3.4. The age range in this condition was between 15 and 18 years. There were 255 female participants, 77 male participants, 1 nonbinary participant, and 1 participant who did not disclose their gender. The experimental procedure involved a total duration of approximately 110 minutes. The procedure included a 15-minute pre-test administered through an online Google form, followed by the 3-part instructional activity described earlier, which lasted 55 minutes. After the instructional activity, there was a 15-minute post-test. The remaining time was dedicated to an informal unstructured interview, where participants were asked to reflect on their experience. The instructor wore the augmented reality headset and shared their view through the Physics laboratory screen, allowing pupils to see the same view as the instructor. One researcher served as the instructor in all sessions to ensure consistency in the experimental conditions. The experimental session was designed to accommodate the instructional activity, assessments, and interview, providing a comprehensive understanding of participants' learning and experiences with the augmented reality system. The qualitative analysis of participant videos aimed to understand how participants communicated with the instructor during the inquiry-based learning activity. To analyze the videos, a coding scheme was developed through an iterative bottom-up coding process. The coding scheme drew inspiration from the four categories of the question-driven problem-based learning framework. The framework was originally designed to measure pupil thinking over multiple weeks and across different mediums, but for this study, the framework was adapted to the context of a 55-minute physics teaching session between a pupil and instructor. The coding scheme consisted of four categories of question types, similar to the framework, which captured the function of the questions: information gathering, bridging and integrating knowledge, extending and exploring beyond the current setting, and reflecting/hypothesizing. Additionally, the coding scheme included codes to track whether a pupil utterance was a request for action or not, as well as whether it referred to a visualization or not. The purpose of these codes was to capture the nature of pupil interactions and their engagement with the augmented reality visualizations. Inter-rater reliability was assessed by having two independent researchers code 30% of the data, with the study condition blinded. The agreement between the coders was measured using relation, and a value of 0.77 was obtained, indicating substantial agreement. The video recordings of all sessions were transcribed, and the coding scheme was applied to analyze the data. The researchers performing the coding were not aware of the study conditions associated with each utterance, although in some cases, it might have been evident from the content of the utterances. In addition to the qualitative analysis, statistical differences between conditions were analyzed using the ANCOVA test. Kolmogorov-Simonov were used to differentiate the sequences of cognitive learning skills between the two study conditions. Overall, the qualitative analysis aimed to provide insights into how participants engaged with the instructor, their questions, and their interactions with the augmented reality system during the instructional activity.

Table 2 – analysis qualitative analysis, the questions posed by the participants categorized into five types

Category	Description
Basic Information	These questions aimed to acquire knowledge about basic concepts. For example, a question like «What is the magnetic electromagnetic waves?» would fall into this category.
Integration	Questions in this category explored the relationships between two or more concepts. An example would be a question like «How does the electromagnetic waves influence the induced force?»
Exploration	These questions extended knowledge beyond the current problem or applied it to novel situations. For instance, a question such as «What happens if the magnet is flipped?» would be classified as an exploration question.
Hypothesis	Questions related to forming or testing hypotheses were categorized as hypothesis questions. An example would be a question like «Does that mean the force is flipped when we flip the magnet?»
Other	This category encompassed all other questions that were not directly related to the learning content, including logistics, communication, or technology-related inquiries. For example, questions like «Will this be on the test?» or «Can we explain what that arrow is?» would be classified as «Other.»

These coding categories and codes were used to analyze the participant videos and understand the nature of the questions asked, the requests made to the instructor, and the references to visual elements in the augmented reality learning experience. In order to understand how augmented reality visual representations are utilized in the learning process, a secondary qualitative analysis was conducted specifically on pupil utterances that involved a visual reference. This analysis focused on inquiries that made reference to visual elements, particularly those related to augmented reality visual representations within the application. The visual elements mentioned by pupils could be either references to physical objects like the magnet or electrical field, or references to the augmented reality visual representations within the application itself. The analysis specifically focused on references to augmented reality visual representations.

Table 3 – Two binary codes assigned to pupil utterances

Types	Description
Learning Gains	A code was assigned when a pupil explicitly requested the instructor to take a specific action. Examples of action requests include asking the instructor to pick up the magnet, pull it again, or flip it
Action Requests	The researchers employed a coding scheme to analyze participants' inquiry styles during the instructional sequence. The coding scheme was designed to identify different inquiry styles, such as structured inquiry, guided inquiry, and open inquiry. Observational data, including video recordings or written transcripts, were used to identify and categorize the inquiry styles exhibited by the participants.
Visual Reference	A code was assigned when the pupil's inquiry referred to a visual element of the learning experience. For instance, if a pupil asked about the behavior of the green and purple arrows or inquired about the appearance of the magnetic field lines for the electrical field, it would be coded as a visual reference.

Table 2 provides a list of the augmented reality visual representations that were coded during this analysis. Each pupil inquiry could refer to zero or more of these representations. Additionally, the analysis also recorded whether the pupil mentioned scientific concepts such as induced force, induced current direction, magnetic electromagnetic waves, etc. Table 3 presents the scientific concepts that were coded during this process. It is important to note that these scientific concepts differ from those initially measured in the pre-post learning tests, as they were identified through pupil utterances. Each pupil inquiry was also associated with one of the five possible Question Types described earlier. If a pupil referred to an augmented reality visual representation or scientific concept without explicitly mentioning it, no code was assigned for the augmented reality visualization or scientific concept. Therefore, a pupil inquiry could contain zero or more augmented reality visual representations, zero or more scientific concepts, and one question type. During the coding process, the researcher was unaware of the study conditions associated with each utterance, although it was possible to identify when a pupil mentioned augmented reality visual representations specific to the augmented reality condition. Since the augmented reality, representations and scientific concepts could be unambiguously identified when explicitly mentioned, no inter-rater reliability was performed, and a single researcher independently coded these dimensions. A qualitative analysis was conducted due to the low number of references in this context. These metrics, including pupil-learning gains, references to augmented reality visual representations, references to scientific concepts, and pupil inquiry styles, are utilized to answer the research questions. Research Question 1, “How is pupil learning affected by increased complexity of augmented reality visualizations?” will be addressed in Section 3.1 using data from these metrics. Subsequently, in Section 3.2, Research Question 2, “How is pupil inquiry affected by increased complexity of augmented reality visualizations?” will be addressed using data from pupil inquiry styles, references to augmented reality visual representations, and references to scientific concepts.

Results

The results for pupil learning gains are presented, analyzing the differences between the two study conditions and examining the influence of augmented reality visualizations on the observed results. The study begins by stating that the initial knowledge level is assumed to be similar between the two conditions, as there was no significant difference in the pretest scores of participants in the augmented reality learning condition (M=9.18, SD = 4.23) and the augmented reality learning condition (M = 7.02, SD = 5.26) (t(42) = -0.57, p=.71).

Table 4 – Codes for augmented reality visual representations, and for scientific concepts present in the activity

Code Type	Example codes
Action Requests	Magnetic N/S poles; Magnetic field lines; graph; Purple arrow; Green arrow; Yellow arrow
Scientific concepts	Magnet poles; Magnetic field lines, shape, or direction; change in fluX; Induced electrical field current; Induced electrical field force; Electrical field induced polarity

The provided information states that the participant relative learning gains scores are displayed in Table 2 and Figure 3. The augmented reality learning participants achieved significantly higher scores than the Augmented reality learning participants in terms of their overall learning score, with a difference of over twice the score. Analyzing specific dimensions of the learning test, it was found that augmented reality learning pupils scored significantly higher on questions related to physical forces. Descriptive statistics suggest that augmented reality learning pupils tend to score higher in their ability to transfer knowledge to new situations. However, the understanding of electrical field current and induced magnetic fields appeared to be similar between the two groups. Regarding communication patterns, it was observed that augmented reality learning participants made significantly more references to visualizations compared to the other group, with roughly double the frequency. This finding suggests that the increased complexity of augmented reality visualizations contributes to improved learning outcomes. However, the specific mechanisms through which augmented reality visualizations are involved in pupils' learning are not clear. It is worth noting that the number of augmented reality visualizations referenced does not directly correspond to the number of questions asked. This discrepancy can be attributed to cases where multiple visualizations were referred to in a single question or instances where pupils were observing visual elements without explicitly mentioning augmented reality. Although the data related to visualizations is limited due to the low number of visual-related questions asked by pupils, it provides some insights into the effects of augmented reality visualizations. Figures 3 and 4 provide insights into the explicit references made by both the augmented reality learning and Augmented reality learning participants to augmented reality visualizations (Figure 3) and scientific concepts (Figure 4). It is observed that the augmented reality visual representation of magnetic field lines was frequently referenced by both groups, which is not surprising considering its continuous visibility throughout the activity in both conditions. Additionally, the augmented reality learning group showed a higher focus on the visuals of purple arrows (representing electromagnetic waves) and green arrows (representing induced forces). Analyzing the concepts mentioned in relation to augmented reality visuals, it was found that the augmented reality learning pupils discussed a larger number of concepts compared to the Augmented reality learning pupils (Table 5).

Table 5 – information about participant relative learning gains scores

Metric	Augmented reality learning Mean	Traditional learning Mean	Standard Deviation	P
Overall Score	0.15	0.33	0.19	0.015
Transfer	0.11	0.23	0.25	0.163
Induced Magnetic Field	0.71	0.63	1.11	0.944
Scientific Concept	0.16	0.20	0.45	0.773
Electrical field	0.03	0.28	0.27	0.22
Current	0.16	0.20	0.45	0.11
Physical Forces	0.21	0.23	031	0.773

The augmented reality learning group, in particular, focused on field shapes, forces, and electromagnetic waves. These findings suggest that the augmented reality visuals facilitate discussions on various concepts, potentially explaining why the augmented reality learning group achieved better learning gains in the topic of forces and overall learning. To further investigate the relationship between augmented reality visualizations and learning, the co-occurrence patterns were analyzed. Figure 6 illustrates the number of questions in which an augmented reality visual representation was mentioned along with a scientific concept. It is observed that each augmented reality visual representation appears to direct pupils' attention to a specific concept, making that concept more visible for pupils to engage with. For instance, the augmented reality visual representation of magnetic field lines is most commonly used to discuss the concept of magnetic field shapes, while the augmented reality green arrow is frequently discussed in relation to induced force. The analysis reveals that when pupils discuss a single visual representation, they often mention different concepts related to that representation. For example, the augmented reality visual representation of magnetic field lines is discussed in relation to induced forces, electromagnetic waves, and polarity. Similarly, the augmented reality green arrow is mentioned when asking about induced current, electromagnetic waves, magnetic field shape, or polarity. This indicates that the augmented reality visualizations serve as prompts for pupils to think about multiple concepts simultaneously. Furthermore, comparing the augmented reality learning and Augmented reality learning groups (Figure 6), it is observed that the different augmented reality visualizations appear to assist augmented reality learning pupils in discussing multiple concepts. This possibility of augmented reality visualizations facilitating the integration of multiple scientific concepts is further supported by the analysis of how multiple scientific concepts are mentioned together (Figure 7). For instance, the concept of the shape of the magnet's field is mentioned in relation to other concepts such as the magnet's poles, electromagnetic waves, and induced forces. The co-occurrence of multiple concepts is more pronounced in the augmented reality learning group, indicating that pupils in that condition engage in thinking about multiple concepts simultaneously. On the other hand, in the Augmented reality learning group, the augmented reality magnetic field lines visualization is never mentioned together with the augmented reality visualization of electrical field current. This suggests that pupils in the Augmented reality learning group may not be utilizing those visualizations to establish connections between the concepts. It is plausible that each augmented reality visual representation serves as an entry point for thinking about different scientific concepts, and the dynamic linking between multiple representations helps augmented reality learning pupils consider a wider range of concepts and their interrelationships. In contrast, the Augmented reality learning group only has access to two augmented reality visual representations that are not dynamically linked. This limited set of visualizations may constrain pupils' thinking to a narrower set of scientific concepts and impede their understanding of the relationships between those concepts. This mechanism potentially explains why pupils in the augmented reality group achieve higher overall learning scores(Table 6).

Table 6 – Single-factor ANOVA individual sessions by gender

№	Variable	Groups	N	Mean	SD	F	η2
1	Academic level and gender	AR(female)	60	309.31	29.55	0.15	0.003
2		Traditional (female)	60	307.39	25.27		
3		AR(female)	60	309.31	27.55	0.15	0.003
4		Traditional (female)	60	307.39	23.27		

Based on the analysis conducted in our study, it can be concluded that none of the factors, including academic level, gender, and the combination of gender and academic level, had any significant influence on the efficiency and productivity of participants in terms of experiment completion time. We examined the effect of augmented reality on the reading performance of physics students by analyzing their pretest and posttest scores in the academic reading test. Table 4 shows the students' overall scores of the pretest and posttest reading performance. Table 7 presents the results of the paired samples t-test scores, which revealed a significant difference between the means of the students' pretest and posttest scores. This indicates that the posttest scores were better than the pretest scores with an effect size of about 53.60%.

Table 7 – Mean and standard deviation of the students' pretest and posttest reading test

Physics Test	Mean	Standard Deviation
Pretest	9.54	1.70
Posttest	15.12	1.57

Table 8 – Results of paired sample t-test for the students' pretest and posttest reading test

Test	Mean	Standard Deviation	df	(t)Value	Significance	Size Effect
Pre-test	1.80	7.37	60	11.201	0.000*	59.77%
Post-test	1.27	11.59				

*Significant at ($\alpha \leq 0.05$).

We examined the effect of augmented reality on the physics performance of physics students by analyzing their pretest and posttest scores in the physics test. Table 8 shows the students' overall pretest and posttest scores of their physics performance. Table 9 shows paired samples t-test scores, which revealed a significant difference between the means of pretest and posttest scores in physics. This shows that the posttest scores were better than that of the posttest scores with an effect size of about 59.77%.

Table 9. shows that there are differences between the mean scores of the students' pretest and posttest physics tests. To test the significance of these differences, paired- samples t-test was used. Table 10 presents the results.

Table 9 – Means and standard deviations of the students' physics pretest and physics posttest test

Physics Test	Mean	Standard Deviation
Pretest	7.38	1.73
Posttest	11.58	1.29

Table 10 – Paired samples t-test results for the students' pretest and posttest physics test

Test	Mean	Standard Deviation	df	(t) Value	Significance	Size Effect
Pretest	1.90	9.37	27	11.301	0.000*	51.35%
Posttest	1.37	15.53				

*Significant at ($\alpha \leq 0.05$).

Table 11 shows that there is a significant difference between the means of the students' pretest and posttest physics scores, with posttest an effect size of about 56.77%. We quantitatively examined the attitudes of physics students toward augmented reality by analyzing students' responses at posttest after the implementation of augmented reality. To specifically address this, descriptive statistics (means and standard deviations) of the students' responses on the attitudes toward using augmented reality questionnaire domains were computed.

Table 11 – Means and standard deviations of students' responses on the posttest scores.

No.	Dependent Variables	Mean*	Standard Deviation	Degree	Rank
1	Attitudes in term of its Ease of Use augmented reality	4.04	0.62	High	1
2	Attitudes in term of its Usefulness augmented reality	3.92	0.78	High	2
3	Attitudes in term of Access augmented reality	3.91	0.64	High	3
	Total	3.94	0.60		

In our study, we investigated the influence of augmented reality visualizations on pupil inquiries and compared the types of inquiries made by participants in different study conditions. We will begin by presenting the differences in inquiries made between the experimental conditions. Then, we will discuss the variations in inquiry patterns observed among the participants. Finally, we will analyze the relationship between augmented reality visualizations and pupil inquiries (Table 11).

Difference in inquiries between experimental conditions In our study, we designed two experimental conditions: one with high complexity augmented reality visualizations and another with low complexity augmented reality visualizations. The participants were randomly assigned to either condition. After engaging with the augmented reality visualizations, they were encouraged to ask questions or seek further information related to the content presented.

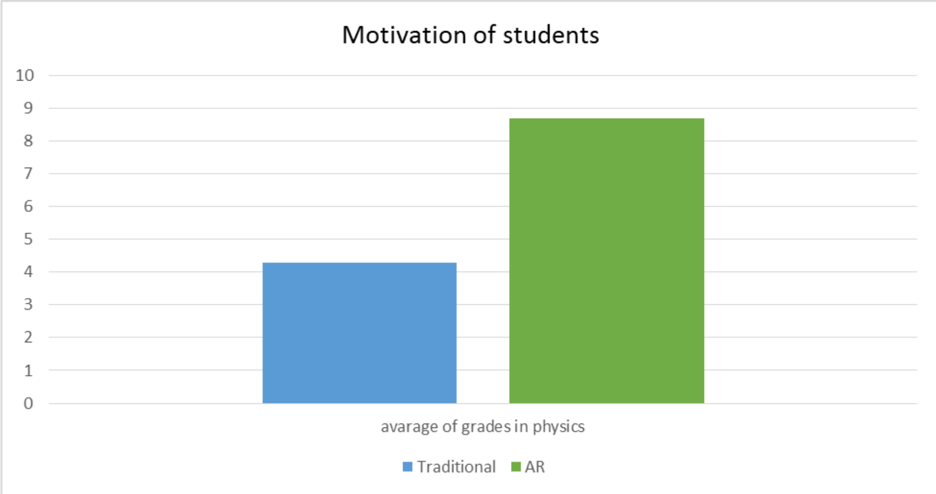

Figure 9 – Test results of experiment for Faraday's Law.

Upon analyzing the inquiries made by participants, we observed notable differences between the two experimental conditions. The participants exposed to high complexity augmented reality visualizations tended to generate more inquiries compared to those exposed to low complexity augmented reality visualizations. This suggests that the complexity of augmented reality visualizations has an impact on the depth and quantity of pupil inquiries. Apart from the overall number of inquiries, we also noticed variations in the patterns of inquiries between the two conditions. Participants in the high complexity augmented reality condition tended to ask more detailed and technical questions related to the intricacies of the content. On the other hand, participants in the low complexity augmented reality condition asked more general and surface-level questions. The differences in inquiry patterns indicate that the complexity of augmented reality visualizations not only affects the quantity of inquiries but also influences the nature and depth of the questions asked. Higher complexity visualizations seem to stimulate a more inquisitive mindset and encourage pupils to delve deeper into the subject matter. Based on our findings, it is evident that augmented reality visualizations play a significant role in shaping pupil inquiries. Higher complexity augmented reality visualizations appear to foster a greater level of curiosity and engagement, leading to more elaborate and technical questions. Conversely, low complexity augmented reality visualizations seem to elicit more basic inquiries that focus on the surface-level aspects of the content.

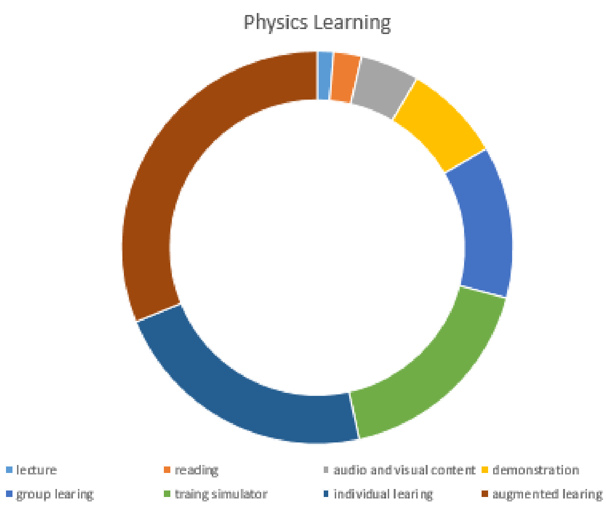

Figure 10 – The effectiveness of the main teaching methods

The results of our study suggest that educators and designers should consider the complexity of augmented reality visualizations when aiming to promote pupil inquiries. By utilizing augmented reality technologies that present more intricate and challenging visualizations, educators can encourage pupils to ask deeper and more meaningful questions, thereby enhancing their understanding and critical thinking skills. It is important to note that our study focused specifically on the impact of complexity in augmented reality visualizations and its relation to pupil inquiries. Further research could explore additional factors that might influence inquiry patterns in augmented reality settings, such as prior knowledge, individual learning styles, and instructional approaches.

Discussion

The findings of the study suggest that access to more complex augmented reality content during high school physics teaching improves pupil learning and enhances the inquiry process. Pupils who had access to more complex augmented reality content showed improved learning outcomes, increased interest in taking actions within the learning activity, and demonstrated a greater likelihood of asking diverse types of inquiry questions. They also showed an inclination to think about a variety of scientific concepts. In contrast, pupils who had exposure to less complex augmented reality content exhibited lower learning outcomes, repetitive inquiries, and a limited ability to use visuals to establish connections between multiple scientific concepts. The availability of more complex augmented reality content enabled pupils to observe the effects of actions more easily and prompted them to make more requests for further action. Furthermore, pupils with access to more complex augmented reality visualizations asked more questions to gather basic information about multiple concepts, engaged in more exploration-oriented questions, and asked fewer questions aimed at integrating knowledge. These results suggest several themes that can be applied to the use of augmented reality in enhancing learning and high school physics teaching. One theme is the provision of multiple points of entry into the learning domain. The presence of augmented reality visualizations makes scientific concepts more visible to pupils, helping them remember and understand these concepts more deeply. Pupils can use augmented reality visualizations to check misunderstandings and fill knowledge gaps. By experiencing visualizations representing different concepts, pupils are stimulated to think about multiple types of concepts, thus having multiple points of entry into the learning domain. The dynamic nature of augmented reality visual representations can illustrate how different scientific concepts behave under different conditions, responding to pupil inquiries. This utilization of augmented reality visualizations in the thinking process creates a distributed cognition system, where the visuals assist pupils in cognitive tasks. The ability to see invisible concepts through augmented reality visualizations reduces the cognitive effort required to understand content from verbal explanations or mental simulations. This reduction in cognitive effort may explain why pupils are more interested in exploring other possibilities when they have greater access to augmented reality visualizations. Future research can explore how augmented reality visualizations offload conceptual information and mediate pupil cognitive load. Additionally, it can investigate why pupils exhibit a greater willingness to explore when observing augmented reality visualizations and examine the impact this has on pupil agency and self-efficacy. Another theme highlighted by the study is the interlinking of scientific concepts and deeper processing. Different forms of representation, including various augmented reality visualizations with different properties, can support pupil learning by highlighting different aspects and relationships between phenomena. The dynamic and linked nature of augmented reality visualizations likely facilitated a richer understanding of the relationships between scientific concepts and encouraged active engagement in exploring those relationships. Observing how certain invisible properties change dynamically together provides pupils with knowledge about the integration of concepts, reducing the need for mental processing of concept integration. Augmented reality visualizations encouraged pupils to understand phenomena from multiple perspectives by prompting them to ask different types of inquiry questions. These finding contrasts with pupils in the condition lacking complex augmented reality content, who were observed to be, stuck asking similar types of inquiry questions and not engaging in complex inquiry. In their study on pupil inquiry styles using traditional pen and paper activities. They found that when pupils persevered and posed questions from multiple perspectives, they achieved a deeper understanding of the learning content. Future work can explore the effectiveness of different types of augmented reality visuals, with an emphasis on dynamically linking multiple scientific concepts together. The passage we provided discusses the potential benefits and implications of using augmented reality in physics teaching at high school. It suggests several areas for future research and highlights some findings from a study. Investigating different modes of representation: The passage suggests exploring how the mode of representation, whether physical objects, virtual 2D simulations, or 3D content in AR, influences the learning of different types of content. This research can help understand the specific role and benefits of augmented reality as a representational medium compared to other mediums like 2D computer displays or immersive 3D augmented reality displays. Communication and active engagement: The study found that pupils used augmented reality visualizations as thinking and communication aids, providing common ground and anchors for their questions to the instructor. Augmented reality was observed to facilitate communication, contribution to problem-solving activities, and active engagement. It increased motivation and curiosity in pupils due to interactive visualizations and the presence of more information. Enhanced teacher-pupil interactions: The presence of complex augmented reality content appeared to encourage pupils and make physics teaching more pupil-driven. This increased motivation and active engagement may lead to greater self-efficacy and confidence in pupils. The passage suggests that further research is needed to validate this hypothesis and understand the impact of augmented reality on teacher-pupil interactions in physics teaching at high school. Implications for 1-1 physics teaching: The passage suggests that augmented reality may become popular in physics teaching, where the instructor wears an augmented reality headset while pupils remotely observe the augmented reality view. This style of teaching could improve accessibility, particularly for pupils in remote or low-income environments, by connecting them to quality instruction. It has the potential to improve educational outcomes for marginalized groups. Future research can explore how this teaching style affects interactions between an instructor and a group of pupils. Factors to consider in augmented reality teaching configurations: The passage acknowledges that the remote nature of the physics teaching session through Physics laboratory may have impacted pupils' sense of agency and control over the learning activity. It suggests comparing these findings with other configurations, such as one instructor teaching multiple pupils in a co-located setting or allowing pupils to access augmented reality content through their own devices or shared screens. We highlight the need for further research to understand the benefits and implications of using augmented reality in physics teaching, including investigating different modes of representation, exploring teacher-pupil interactions, and examining various teaching configurations.

Limitations

The current research indeed has several limitations that should be considered. Firstly, the two-condition study design used in the research makes it difficult to identify the specific impacts of the different aspects of complexity between conditions. The complexity variations included differences in anchoring of augmented reality representations, the number of augmented reality representations, and the types of augmented reality representations. Future research should aim for more controlled variations along these specific dimensions to gain a better understanding of their individual effects. The low sample size in the study reduces the statistical power, limiting the ability to detect significant differences between conditions. As a result, the results and discussions provided are somewhat speculative and should be seen as directions for future research. Conducting the study with a larger number of participants engaged in a more open-ended physics teaching activity over an extended period could potentially yield more robust statistical effects. The instructional activity used in the study contained a limited number of prompts for pupil questions, which may have resulted in a low number of pupil questions overall. A more extensive range of statistical effects could potentially be observed by incorporating a larger number of participants and providing them with more opportunities for inquiry and questioning. The qualitative analysis of pupil mentions of augmented reality visuals in the study was limited to visual questions explicitly mentioning the visuals.

Conclusion

In this study, the focus was specifically on investigating how increased complexity of augmented reality content influences learning and inquiry in high school physics teaching, with a particular emphasis on electromagnetism concepts such as Faraday's Law and Lenz's Law. To facilitate the teaching sessions, the researchers developed an augmented reality tool that instructors could use. The tool incorporated multiple dynamically changing 3D visualizations that were anchored and moved with real objects in the physical environment. This high complexity augmented reality application was compared to a lower complexity application that utilized only a few 2D representations that did not move with the real objects. A between-subjects study design was employed, meaning that different groups of pupils were exposed to different levels of complexity in the augmented reality content. The study aimed to compare the learning outcomes, inquiry styles, and engagement levels between these groups. The results of the study indicated that pupils who experienced the higher complexity augmented reality content demonstrated better learning outcomes compared to those exposed to the lower complexity application. These pupils also exhibited a wider variety of inquiry styles, indicating increased engagement and exploration in their learning activities. Furthermore, the augmented reality visual representations appeared to stimulate pupils to think about multiple types of scientific concepts, enabling them to make connections and relationships between these concepts. The high complexity augmented reality content encouraged a more active engagement from pupils, as they were willing to explore and take actions during the learning activities. These findings highlight the potential of augmented reality technology, particularly when utilizing complex visualizations, to enhance learning experiences in physics education. By providing dynamic and interactive representations, augmented reality can stimulate pupils' thinking, facilitate conceptual understanding, and foster active engagement. The study suggests that integrating advanced augmented reality tools in high school physics teaching can have a positive impact on pupil learning outcomes and inquiry skills. However, further research is needed to explore the underlying mechanisms and to validate these findings in different educational contexts.

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No potential conflict of interest was reported by the authors.

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1. Ozdamli, F., & Hursen, C. An Emerging Technology: Augmented Reality to Promote Learning // International Journal of Emerging Technologies in Learning. – 2017. – №12 (11). – С. 121–137. https://doi.org/10.3991/ijet.v12i11.7354

2. Kaur, D. P., Mantri, A., & Horan, B. Enhancing student motivation with use of augmented reality for interactive learning in engineering education // Procedia Computer In physics lesson. – 2020. –№172. – С. 881–885. https://doi.org/10.1016/j.procs.2020.05.127.

3. Chen, C.-H., Yang, C.-K., Huang, K., Yao, K.-C. Augmented reality and competition in robotics education: Effects on 21st century competencies, group collaboration and learning motivation // Journal of Computer Assisted Learning. –2020. – №36 (3). – С. 1052-1062. https://doi.org/10.1111/jcal.12469/v2/response1

4. Moro, C. Phelps, C. Redmond, P. Stromberga, Z. HoloLens and mobile augmented reality in medical and health in physics lesson education: A randomized controlled trial // British Journal of Educational Technology. –2021. –№52 (2). – С. 680-694. https://doi.org/10.1111/bjet.13049

5. Chou, Y.-Y., Wu, P.-F., Huang, C.-Y., Chang, S.-H., Huang, H.-S., Lin, W.-M., Lin, M.-L.. Effect of digital learning using augmented reality with multidimensional concept map in elementary in physics lesson // The Asia-Pacific Education Researcher. –2021. –№31. – С. 383-393. https://doi.org/10.1007/s40299-021-00580-y

6. Chang, Y.-S., Chen, C.-N., Liao, C.-L. Enhancing English-learning performance through a simulation classroom for students using augmented reality—a junior high school case study // Applied In physics lessons. – 2020. –№10(21). – С. 7854. https://doi.org/10.3390/app10217854

7. Demitriadou, E., Stavroulia, K., Lanitis, A. Comparative evaluation of virtual and augmented reality for teaching mathematics in primary education // Education and Information Technologies. –2020. –№25(1). – С. 381-401. https://doi.org/10.1007/s10639-019-09973-5

8. Zhang, J., Huang, Y.-T., Liu, T.-C., Sung, Y.-T., Chang, K.-E. Augmented reality worksheets in field trip learning // Interactive Learning Environments. –2020. –№7. – С. 1-18. https://doi.org/10.1080/10494820.2020.1758728

9. Huang, H.-M., Huang, T.-C., Cheng, C.-Y. Reality matters? Exploring a tangible user interface for augmented-reality-based fire education // Universal Access in the Information Society. –2021. –№35. – С. 127. https://doi.org/10.1007/s10209-021-00808-0

10. Chin, K.-Y., Wang, C.-S. Effects of augmented reality technology in a mobile touring system on university students' learning performance and interest // Australasian Journal of Educational Technology. – 2021. –№37 (1). – C. 27-42. https://doi.org/10.14742/ajet.5841

11. Buchner, J. Generative learning strategies do not diminish primary students' attitudes towards augmented reality // Education and Information Technologies. – 2021. –№27 (1). – C. 701-717, https://doi.org/10.1007/s10639-021-10445-y

12. Arymbekov B. S., Turekhanova K. M., Alipbayev D. D., Tursanova E. R., Suprapto N. The effect of using Geogebra software for augmented reality visualization to teach physics in high school // Farabi Journal of Social Sciences. – 2023. –№ 9(2). https://doi.org/10.26577/FJSS.2023.v9.i2.06

13. Cai, S., Liu, C., Wang, T., Liu, E., Liang, J.-C. Effects of learning physics using augmented reality on students' self-efficacy and conceptions of learning // British Journal of Educational Technology. –2021. –№52 (1). – C. 235-251. https://doi.org/10.1111/bjet.13020

14. Garzón J. et al. How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis //Educational Research Review. – 2020. – T. 31. – C. 100334. https://doi.org/10.1016/j.edurev.2020.100334

15. Thees M. et al. Effects of augmented reality on learning and cognitive load in university physics laboratory courses //Computers in Human Behavior. – 2020. – T. 108. – C. 106316.https://doi.org/10.1016/j.chb.2020.106316

16. Eldokhny A. A., Drwish A. M. Effectiveness of augmented reality in online distance learning at the time of the COVID-19 pandemic //International Journal of Emerging Technologies in Learning (Online). – 2021. – T. 16. – №. 9. – C. 198.. https://doi.org/10.3991/ijet.v16i09.17895

17. Arymbekov, B. S., Turekhanova, K. M., Alipbayev, D. D., Tursanova, E. R. Development of augmented reality application for physics and geophysics laboratory // Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-5/W2-2023. – 2023. – №17. – C. 19–24, https://doi.org/10.5194/isprs-archives-XLVIII-5-W2-2023-19-2023

18. Guntur, M.I., Setyaningrum, W. The effectiveness of augmented reality in learning vector to improve students' spatial and problem-solving skills // International Journal of Inter-active Mobile Technologies. – 2021. – №15. – C 159-173, https://doi.org/10.3991/ijim.v15i05.19037

19. Marini, A., Nafisah, S., Sekaringtyas, T., Safitri, D., Lestari, I., Suntari, Y., Umasih, Sudrajat, A., & Iskandar, R. Mobile Augmented Reality Learning Media with Metaverse to Improve Student Learning Outcomes in Science Class // International Journal of Interactive Mobile Technologies. – 2022. – №16 (07). – C. 99–115. https://doi.org/10.3991/ijim.v16i07.25727

20. Hsieh, M.-C. Development and application of an augmented reality oyster learning system for primary marine education // Electronics. – 2021. – №10 (22). – C. 2818, https://doi.org/10.3390/electronics10222818

21. Sahin D., Yilmaz R. M. The effect of Augmented Reality Technology on middle school students' achievements and attitudes towards science education //Computers & Education. – 2020. – T. 144. – C. 103710. https://doi.org/10.1016/j.compedu.2019.103710

22. Lee, C.-J. Hsu, Y. Sustainable education using augmented reality in vocational certification lessons // Sustainability. – 2021. – №13 (11), – C.6434. https://doi.org/10.3390/su13116434

23. Christopoulos, A., Pellas, N., Kurczaba, J., Macredie, R. The effects of augmented reality-supported instruction in tertiary-level medical education // British Journal of Education-al Technology. – 2021. – №53 (2). – C. 307-325. https://doi.org/10.1111/bjet.13167

24. Suhaizal, H., Abdul Rahman, K. A., Khamis, N., Shukor, U. H., Che Lah, N. H., & Zulkifli, N. N. The Design and Development of Augmented Reality (AR) Application for Internet Evolution Learning Topics // International Journal of Interactive Mobile Technologies. – 2023. – №17(05). – C. 162–181. https://doi.org/10.3991/ijim.v17i05.36483

25. Wahyu, Y., Suastra, I.W., Sadia, I.W., Suarni, N.K. The effectiveness of mobile augmented reality assisted STEM-based learning on scientific literacy and students' achievement // International Journal of Instruction. – 2020. – №13 (3). – C. 343-356. https://doi.org/10.29333/iji.2020.13324a

26. Alqarni, T. Comparison of augmented reality and conventional teaching on special needs students' attitudes towards in physics lesson and their learning outcomes // Journal of Baltic In physics lesson Education. – 2021. – T. 20 (4). – pp. 558-572. https://doi.org/10.33225/jbse/21.20.558

27. Мухтарқызы К., Абильдинова Г.М. Толықтырылған шынайылық мобильді қосымшаларының оқушылардың оқу мотивациясына әсері. // «ҚР ҰҒА хабаршысы» ғылыми журналы. – 2023. – №1. – С. 201-211. https://doi.org/10.32014/2023.2518-1467.432

28. Арымбеков Б.С., Туреханова К.М. Орта мектепке бағдарланған физика пәніне арналған толықтырылған шынайылық қосымшасын қолдану әдістемесін зерттеу // ҚазҰУ хабаршысы. Педагогикалық серия. – 2023. – № 76(3). – С. 125-145. https://doi.org/10.26577/JES.2023.v76.i3.011

29. Nurbekova, Z., & Baigusheva, B. On the Issue of Compliance with Didactic Principles in Learning using Augmented Reality // International Journal of Emerging Technologies in Learning. – 2020. – №15 (15), – C. 121–132. https://doi.org/10.3991/ijet.v15i15.14399

30. Elmira, O., Rauan, B., Dinara, B., & Prevalla, T., Etemi, B. The Effect of Augmented Reality Technology on the Performance of University Students // International Journal of Emerging Technologies in Learning. – 2022. – №17 (19). – C. 33–45. https://doi.org/10.3991/ijet.v17i19.32179

31. Eldokhny, A.A., Drwish, A.M. Effectiveness of augmented reality in online distance learning at the time of the COVID-19 pandemic // International Journal of Emerging Technologies in Learning. – 2021. – №16. – C. 198-218.https://doi.org/10.3991/ijet.v16i09.17895

32. Arymbekov, B.S. Augmented Reality Application to Support Visualization of Physics Experiments // 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST), Astana, Kazakhstan. – 2023. – №2. – С. 52-55. https://doi.org/10.1109/SIST58284.2023.10223534

33. Afnan, K., Muhammad, N., Khan, Lee, M.-Y., A. Imran, Sajjad, M. School of the future: A comprehensive study on the effectiveness of augmented reality as a tool for primary school children's education // Applied In physics lessons. – 2021. – №11. – С. 5277. https://doi.org/10.3390/app11115277

34. Weng, C., Otanga, S., Christianto, S.M., Chu, R.J.-C. Enhancing students' biology learning by using augmented reality as a learning supplement // Journal of Educational Computing Research. – 2020. – №58(4). – С. 747-770 https://doi.org/10.1177/0735633119884213

35. Арымбеков Б.С., Турeханова К.М. Физика пәнін саналы оқытуда толықтырылған шынайлықты оқыту құралы ретінде қарастыру // ҚазҰУ хабаршысы. Педагогикалық серия. – 2022. – №73(4). – С. 128-141. https://doi.org/10.26577/JES.2022.v73.i4.12

36. Sugandi, M., Juharyanto, Wena, M., & Sutrisno, N. Essential Competence as a Determiner of Learning Media Development in Network-Based on 3D Augmented Reality in the Pre-Teacher Civil Engineering Education Study Program // International Journal of Inter-active Mobile Technologies. – 2022. – №16 (05). – pp. 199–206. https://doi.org/10.3991/ijim.v16i05.28999

37. Арымбеков Б.С., Турeханова К.М. Толықтырылған шынайылықты физика пәнінің зертханалық жұмыстарында ұтымды қолдану әдістемесі // Торайғыров университетінің хабаршысы: педагогикалық сериясы. – 2023. – № 3. – С. 157-169. https://doi.org/10.48081/POLK7321

38. Сайтнабиева С. З., Сарыбаева А. Х., Усембаева И. Б. Физика құбылыстарын түсінуде AR технологиясын қолдануға мүмкіндік беретін мобильді қосымшаларды пайдалану // Қ.А.Ясауи атындағы Халықаралық қазақ-түрік университетінің хабарлары. – 2023. – № 27. – С. 17-25. https://doi.org/10.47526/2023-4/2524-0080.05C

39. Бауыржан, С., Адамова, А. Толықтырылған шынайылық технологияларын қолдану негізінде ақпаратты өңдеу және визуализациялау // Технические науки: Проблемы и решения, Интернаука. . – 2021. – №1(41). – С. 96. https://elibrary.ru/item.asp?id=44781123

40. Aviandari, S., Suprapto, N., & Arymbekov, B. Exploration of Socio-Scientific Issues through Coffee Brewing Methods to Explore Physics Literacy: Place Based Education at SK Coffee Lab Kediri // Studies in Philosophy of Science and Education. 2022. №3 (1). – pp. 41-51. https://doi.org/10.46627/sipose.v3i1.303

References

Afnan, K., Muhammad, N., Khan, Lee, M.-Y., A. Imran, & Sajjad, M. (2021). School of the future: A comprehensive study on the effectiveness of augmented reality as a tool for primary school children's education. *Applied In physics lessons*, 11(11). 5277. https://doi.org/10.3390/app11115277

Allcoat, D., Hatchard, T., Azmat, F., Stansfield, K., Watson, D., & Von Mühlenen, A. (2021). Education in the digital age: Learning experience in virtual and mixed realities. *Journal of Educational Computing Research*, 59 (5), 795-816. https://doi.org/10.1177/0735633120985120

Alqarni, T. (2021). Comparison of augmented reality and conventional teaching on special needs students' attitudes towards in physics lesson and their learning outcomes. *Journal of Baltic In physics lesson Education,* 20 (4), 558-572. https://doi.org/10.33225/jbse/21.20.558

Arymbekov, B.S. (2023). Augmented Reality Application to Support Visualization of Physics Experiments. 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST), Astana, Kazakhstan, 52-55. https://doi.org/10.1109/SIST58284.2023.10223534

Arymbekov, B. S., & Turekhanova, K. M., Alipbayev, D. D., Tursanova, E. R. (2023). Development of augmented reality application for physics and geophysics laboratory, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-5/W2-2023, 19–24, https://doi.org/10.5194/isprs-archives-XLVIII-5-W2-2023-19-2023

Arymbekov B.S., & Turekhanova K.M. (2023). Toliqtirilgan shynayiliqti fïzïka panining zertxanaliq jumistarinda utimdi qoldanw adistemesi [Methodology of rational use of augmented reality in laboratory works of physics.] *Toraygyrov University Bulletin: Pedagogical Series,* vol. 9(3). pp. 9-21. https://doi.org/10.48081/POLK7321

Arymbekov, B.S., & Turekhanova, K.M. (2022). Fizika panin sanali oqituda toliqtirilgan shinailiqti oqitu qurali retinde qarastiru. [Observation of Augmented Reality in Teaching Physics as a tool of Intellectual Teaching.] *Journal of Educational Sciences*, vol. 73(4), pp. 128-141. https://doi.org/10.26577/JES.2022.v73.i4.12

Arymbekov, B. S., & Turekhanova, K. M. (2023). Orta mektepke bagdarlangan fïzika panine arnalgan tolıqtırılgan şınayılıq qosımşasın qoldanw adistemesin zerttew [Study of the progress of using augmented reality application for teaching physics in high school.] *Journal of Educational Sciences*, 76(3), 128-145. https://doi.org/10.26577/JES.2023.v76.i3.01 (in Kazakh)

Arymbekov B. S., Turekhanova K. M., Alipbayev D. D., Tursanova E. R., & Suprapto N. (2023). The effect of using Geogebra software for augmented reality visualization to teach physics in high school. *Farabi Journal of Social Sciences*, 9(2). 15-35. https://doi.org/10.26577/FJSS.2023.v9.i2.06

Aviandari, S., Suprapto, N., & Arymbekov, B. (2022). Exploration of Socio-Scientific Issues through Coffee Brewing Methods to Explore Physics Literacy: Place Based Education at SK Coffee Lab Kediri*. Studies in Philosophy of Science and Education*, 3(1), 41-51. https://doi.org/10.46627/sipose.v3i1.303

Baurzhan, S., Adamova, A. (2021). Tolıqtırılgan şınayılıq tehnologiyaların qoldanw negizinde aqparattı ondew jane vizwalizaciyalaw [Processing and visualization of information based on the use of augmented reality technologies]. Technical sciences: Problems and solutions, Vol. 1(41). No. 96. https://elibrary.ru/item.asp?id=44781123 (in Kazakh)

Buchner, J. (2021). Generative learning strategies do not diminish primary students' attitudes towards augmented reality. *Education and Information Technologies*, 27 (1). 701-717. https://doi.org/10.1007/s10639-021-10445-y

Cai, S., Liu, C., Wang, T., Liu, E., & Liang, J.-C. (2021). Effects of learning physics using augmented reality on students' self-efficacy and conceptions of learning. *British Journal of Educational Technology*, 52 (1). 235-251, https://doi.org/10.1111/bjet.13020

Chang, Y.-S., Chen, C.-N., & Liao, C.-L. (2020). Enhancing English-learning performance through a simulation classroom for students using augmented reality—a junior high school case study. *Applied Sciences*, 10 (21). 7854, https://doi.org/10.3390/app10217854

Chen, C.-H., Yang, C.-K., Huang, K., & Yao, K.-C. (2020). Augmented reality and competition in robotics education: Effects on 21st century competencies, group collaboration and learning motivation. *Journal of Computer Assisted Learning*, 36 (3). 1052-1062. https://doi.org/10.1111/jcal.12469/v2/response1

Chin, K.-Y., Lee, K.-F., & Chen, Y.-L. (2020). Effects of a ubiquitous guide-learning system on cultural heritage lesson students' performance and motivation. *IEEE Transactions on Learning Technologies,* 13 (1). 52-62. https://doi.org/10.1109/tlt.2019.2926267

Chin, K.-Y., & Wang, C.-S. (2021). Effects of augmented reality technology in a mobile touring system on university students' learning performance and interest. *Australasian Journal of Educational Technology,* 37 (1). 27-42. https://doi.org/10.14742/ajet.5841

Chou, Y.-Y., Wu, P.-F., Huang, C.-Y., Chang, S.-H., Huang, H.-S., Lin, W.-M., Lin, M.-L. (2021). Effect of digital learning using augmented reality with multidimensional concept map in elementary in physics lesson. *The Asia-Pacific Education Researcher,* 31(1). 383-393. https://doi.org/10.1007/s40299-021-00580-y

Christopoulos, A., Pellas, N., Kurczaba, J., & Macredie, R. (2021). The effects of augmented reality-supported instruction in tertiary-level medical education. *British Journal of Educational Technology*, 53 (2). 307-325. https://doi.org/10.1111/bjet.13167

Demitriadou, E., Stavroulia, K., & Lanitis, A. (2020). Comparative evaluation of virtual and augmented reality for teaching mathematics in primary education. *Education and Information Technologies*, 25 (1). 381-401. https://doi.org/10.1007/s10639-019-09973-5

Eldokhny, A.A., & Drwish, A.M. (2021). Effectiveness of augmented reality in online distance learning at the time of the COVID-19 pandemic. *International Journal of Emerging Technologies in Learning*, 16(1). 198-218. https://doi.org/10.3991/ijet.v16i09.17895

Elmira, O., Rauan, B., Dinara, B., & Prevalla, T., & Etemi, B. (2022). The Effect of Augmented Reality Technology on the Performance of University Students. *International Journal of Emerging Technologies in Learning*, 17(19), 33–45. https://doi.org/10.3991/ijet.v17i19.32179

Eldokhny, A. A., & Drwish, A. M. (2021). Effectiveness of Augmented Reality in Online Distance Learning at the Time of the COVID-19 Pandemic. *International Journal of Emerging Technologies in Learning,* 16(09). 198–218. https://doi.org/10.3991/ijet.v16i09.17895

Garzón, J., Kinshuk, T., Baldiris, S., Gutiérrez, J., & Pavón, J. (2020). How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis. *Educational Research Review*, 31(1). 320-334. https://doi.org/10.1016/j.edurev.2020.100334

Guntur, M.I., & Setyaningrum, W. (2021). The effectiveness of augmented reality in learning vector to improve students' spatial and problem-solving skills. *International Journal of Interactive Mobile Technologies*, 15(2). 159-173. https://doi.org/10.3991/ijim.v15i05.19037

Hsieh, M.-C. (2021). Development and application of an augmented reality oyster learning system for primary marine education. *Electronics*, 10 (22).2801-2818. https://doi.org/10.3390/electronics10222818

Huang, H.-M., Huang, T.-C., & Cheng, C.-Y. (2021). Reality matters? Exploring a tangible user interface for augmented-reality-based fire education. *Universal Access in the Information Society,* 21(1). 927–939. https://doi.org/10.1007/s10209-021-00808-0

Lee, C.-J. & Hsu, Y. (2021). Sustainable education using augmented reality in vocational certification lessons. *Sustainability*, 13 (11). 6434. https://doi.org/10.3390/su13116434

Kaur, D. P., Mantri, A., & Horan, B. (2020). Enhancing student motivation with use of augmented reality for interactive learning in engineering education. *Procedia Computer In physics lesson*, 172(1). 881–885. https://doi.org/10.1016/j.procs.2020.05.127.

Moro, C. Phelps, C. Redmond, P. & Stromberga, Z. (2021). HoloLens and mobile augmented reality in medical and health in physics lesson education: A randomised controlled trial. *British Journal of Educational Technology*, 52 (2). 680-694 https://doi.org/10.1111/bjet.13049

Marini, A., Nafisah, S., Sekaringtyas, T., Safitri, D., Lestari, I., Suntari, Y., Umasih, Sudrajat, A., & Iskandar, R. (2022). Mobile Augmented Reality Learning Media with Metaverse to Improve Student Learning Outcomes in Science Class. *International Journal of Interactive Mobile Technologies*, 16(07). 99–115. https://doi.org/10.3991/ijim.v16i07.25727

Mukhtarovna K. & Abildinova G.M. (2023). Toliqtirilgan shinayiliq mobildi qosimshalarining oqwşilarding oqw motïvacïyasina äseri [Impact of Augmented Reality mobile applications on students' learning motivation]. *Scientific journal "Vestnik NAN RK",* vol. 401(1). pp. 201-211 https://doi.org/10.32014/2023.2518-1467.432(in Kazakh)

Nurbekova, Z., & Baigusheva, B. (2020). On the Issue of Compliance with Didactic Principles in Learning using Augmented Reality. *International Journal of Emerging Technologies in Learning,* 15(15), 121–132. https://doi.org/10.3991/ijet.v15i15.14399

Ozdamli, F., & Hursen, C. (2017). An Emerging Technology: Augmented Reality to Promote Learning. *International Journal of Emerging Technologies in Learning*, 12(11), 121–137. https://doi.org/10.3991/ijet.v12i11.7354

Saitnabieva S. Z., Sarybaeva A. Kh., & Usembayeva I. B. (2023). Fïzïka qubilistarin tüsinwde ar texnologïyasin qoldanwğa mümkindik beretin mobïldi qosimşalardi paydalanu [Using mobile applications that allow to use ar technology in understanding physical phenomena]. *News of the International Kazakh-Turkish University named after K.A.Yasaui*. 4(27). 53-64. https://doi.org/10.47526/2023-4/2524-0080.05 (in Kazakh)

Sahin, D., & Yilmaz, R.M. (2020). The effect of augmented reality technology on middle school students' achievements and attitudes towards in physics lesson education. *Computers & Education,* 144(1). https://doi.org/10.1016/j.compedu.2019.103710

Sugandi, M., Juharyanto, Wena, M., & Sutrisno, N. (2022). Essential Competence as a Determiner of Learning Media Development in Network-Based on 3D Augmented Reality in the Pre-Teacher Civil Engineering Education Study Program. *International Journal of Inter-active Mobile Technologies*, 16(05), 199–206. https://doi.org/10.3991/ijim.v16i05.28999

Suhaizal, H., Abdul Rahman, K. A., Khamis, N., Shukor, U. H., Che Lah, N. H., & Zulkifli, N. N. (2023). The Design and Development of Augmented Reality (AR) Application for Internet Evolution Learning Topics. *International Journal of Interactive Mobile Technologies*, 17(05), 162–181. https://doi.org/10.3991/ijim.v17i05.36483

Thees, M., Kapp, S., Strzys, M.P., Beil, F., Lukowicz, P., & Kuhn, J. (2020). Effects of augmented reality on learning and cognitive load in university physics laboratory lessons. *Computers in Human Behavior*, 108(1). 106-116. https://doi.org/10.1016/j.chb.2020.106316

Wahyu, Y., Suastra, I.W., Sadia, I.W., & Suarni, N.K. (2020). The effectiveness of mobile augmented reality assisted STEM-based learning on scientific literacy and students' achievement. *International Journal of Instruction*, 13 (3). 343-356. https://doi.org/10.29333/iji.2020.13324a

Weng, C., Otanga, S., Christianto, S.M., & Chu, R.J. – C. (2020). Enhancing students' biology learning by using augmented reality as a learning supplement. *Journal of Educational Computing Research*, 58 (4). 747-770. https://doi.org/10.1177/0735633119884213

Zhang, J., Huang, Y.-T., Liu, T.-C., Sung, Y.-T., & Chang, K.-E. (2020). Augmented reality worksheets in field trip learning. *Interactive Learning Environments*, 31(1), 4-21. https://doi.org/10.1080/10494820.2020.1758728

Авторлар туралы мәлімет:

Арымбеков Бекен Сагатбекович (корреспондент автор) – PhD доктор, плазма физикасы, нанотехнология және компьютерлік физика кафедрасының профессоры, Әл-Фараби атындағы Қазақ ұлттық университеті (Алматы қ., Қазақстан, эл. пошта:beckemn@mail.ru)

Туреханова Кундуз Моминовна – физика-математика ғылымдарының кандидаты, плазма физикасы, нанотехнология және компьютерлік физика кафедрасының қауымдастырылған профессоры, Әл-Фараби атындағы Қазақ ұлттық университеті (Алматы, Қазақстан, эл.пошта:kunduz@physics.kz) .

Камил Федус – PhD доктор, физика, астрономия және информатика факультетінің профессоры, Николай Коперник университеті (Торун, Польша, эл.пошта: kamil@fizyka.umk.pl)

Нади Супрапто – PhD доктор, физика кафедрасының профессоры, Сурабая мемлекеттік университеті Сурабая, Индонезия эл.пошта: nadisuprapto@unesa.ac.id

Мұса Тұрдалыұлы – PhD доктор, ақпараттық технологиялар факультетінің профессоры, Қ.И. Сәтбаев атындағы Қазақ ұлттық зерттеу техникалық университеті (Алматы, Қазақстан эл.пошта: m.turdalyuly@gmail.com)

Эльмира Тұрсанова – PhD доктор, математика кафедрасының профессоры, Қ.И. атындағы Қазақ ұлттық зерттеу техникалық университеті. Сәтбаев, Алматы, Қазақстан, эл.пошта: tursanovae@gmail.com)

Сведения об авторах:

Арымбеков Бекен (корреспондентный автор) – PhD доктор, профессор кафедры физики плазмы, нанотехнологии и компьютерной физики, Казахский национальный университет имени аль-Фараби (Алматы, Казахстан. эл.пошта: beckemn@mail.ru)

Туреханова Кундуз – кандидат физико-математических наук, ассоциированный профессор кафедры физики плазмы, нанотехнологии и компьютерной физики, Казахский национальный университет имени аль-Фараби (Алматы, Казахстан. эл.пошта: kunduz@physics.kz)

Камил Федус – PhD доктор, профессор факультета физики, астрономии и информатики, Университет Николая Коперника, (Торунь, Польша, эл.пошта: kamil@fizyka.umk.pl)

Нади Супрапто – PhD доктор, профессор кафедры физики, Государственный университет Сурабаи (Сурабая, Индонезия эл.пошта: nadisuprapto@unesa.ac.id)

Мусса Турдалулы – PhD доктор, профессор факультета информационных технологий, Казахский национальный исследовательский технический университет им. К.И. Сатпаева (Алматы, Казахстан, эл.пошта: m.turdalyuly@gmail.com)

Эльмира Турсанова– PhD доктор, профессор кафедры математики, Казахский национальный исследовательский технический университет им. К.И. Сатпаева (Алматы, Казахстан, эл.пошта: tursanovae@gmail.com)

Information about authors:

Arymbekov Beken (corresponding author) – PhD, professor of Department of Plasma Physics, Nanotechnology and Computer Physics Al-Farabi Kazakh National University (Almaty, Kazakhstan, email: beckemn@mail.ru)

Turekhanova Kunduz – Candidate of Physics and Mathematics Sciences, associate professor of Department of Plasma Physics, Nanotechnology and Computer Physics, Al-Farabi Kazakh National University (Almaty, Kazakhstan. email: kunduz@physics.kz)

Kamil Fedus – PhD, professor of Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University (Toruń, Poland, email: kamil@fizyka.umk.pl)

Nadi Suprapto – PhD, Professor of Department of Physics, the State University of Surabaya (Surabaya, Indonesia, email: nadisuprapto@unesa.ac.id)

Mussa Turdalyuly – PhD, professor of Faculty of Information technology, Kazakh National Research Technical University named after K.I. Satpayev (Almaty, Kazakhstan, email: m.turdalyuly@gmail.com)

Elmira Tursanova – PhD, professor of department of mathematics, Kazakh National Research Technical University named after K.I. Satpayev (Almaty, Kazakhstan, email: tursanovae@gmail.com)

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