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# Pedagogical Innovations in the Use of Virtual Reality for Educational Purposes: An Experimental Study

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## ABSTRACT

The aim of the study was to identify the characteristics of innovation in the use of virtual reality within the educational process in Bulgaria. The methodology involved a comparative analysis to assess the effectiveness of virtual reality, a pedagogical experiment to integrate virtual reality into the educational process and observe its impact on student learning outcomes, as well as the development of an algorithm for the effective implementation of virtual reality in education in Bulgaria. As a result of the study, it was found that the experimental group employing virtual reality in teaching achieved higher outcomes than the control group utilising traditional methods. This study demonstrates the effectiveness of integrating virtual reality into the educational process, as the technology contributes to deeper comprehension of the material and increased student motivation. It was observed that in Bulgaria, Ukraine, and Thailand, the adoption of innovative technologies such as virtual reality can significantly enhance the quality of education. The results of the experiment indicated that the use of virtual reality technologies in the educational process significantly increased student motivation and engagement. Students in the experimental group demonstrated higher results in tasks related to interactive lesson planning and using virtual reality to study complex concepts, compared to the control group, which only used traditional teaching methods. Three approaches were identified: developing VR-based courses to enhance student engagement, training educators for proper implementation, and providing institutions with the necessary equipment and software for effective VR use. The implementation of these measures will contribute to improving the quality of education in Bulgaria, Ukraine, and Thailand and better prepare students to meet the modern demands of the professional environment. The practical significance of the study lies in its confirmation of the effectiveness of virtual reality in education, particularly in enhancing student motivation and engagement.

**Keywords:** Virtual reality integration in education, Pedagogical experiment, Cross-country comparison (Bulgaria–Ukraine–Thailand), Student motivation enhancement, Teacher professional development for VR

## Introduction

Pedagogical innovations, particularly the use of virtual reality (VR) for educational purposes, offer new prospects for the educational process. Specifically, they enable the creation of interactive environments that closely simulate real-world conditions, thereby enhancing knowledge acquisition and the development of practical skills among students. The relevance of this approach lies in the fact that traditional teaching methods often lack the flexibility and individualisation required for the effective training of qualified specialists. In the context of rapid changes in the labour market, student career guidance plays a vital role in preparing learners for future professional activities. A key component of this process is the training of teachers in higher education institutions (HEIs), who must possess a sufficient level of competence in the use of emerging technologies such as VR. Preparing teachers for the effective use of virtual reality involves acquiring technical skills and developing pedagogical methodologies that ensure the integration of these technologies into academic curricula. This, in turn, contributes to improving the overall quality of education and enhancing the competitiveness of graduates.

The issue of pedagogical innovations in the use of VR for educational purposes in Bulgaria is being actively studied by scholars, with various aspects receiving attention. Georgieva-Tsaneva and Serbezova[1], Barreiras et al.[2] examined the use of VR technologies and games in distance learning in Bulgaria. Their research concentrated on the utilisation of VR platforms, including clinical simulations for medical students, which facilitate the development of authentic learning scenarios without necessitating physical presence in medical institutions. They also explored the impact of serious games designed to enhance motivation and engage students in active learning. Interactive courses and resources on e-learning platforms further support self-directed learning, allowing students to explore material independently and thereby improve their knowledge and practical skills in key areas of sustainable development.[3,4] Mishkova-Yotova and Peneva[5], Lin et al.[6] studied the use of project-based learning through VR/AR technologies and 3D learning experiences in classroom settings. Their research focused on the impact of such technologies in enhancing students' engagement with learning content, developing practical skills, and facilitating the comprehension of complex subjects through virtual immersion.

In their study, Ding and Hao[7] investigated the use of augmented reality (AR) in Bulgarian schools, focusing particularly on its potential to enhance the learning process and increase students' interest in education, especially in the natural sciences. They highlighted that AR can stimulate interactive learning, facilitate the comprehension of complex concepts, and promote the development of critical thinking. Slagle et al.[8] Topalska[9] analysed the role of virtual and augmented reality as tools for educational development, particularly in the context of technological innovation in the educational process. The author explored the potential of these technologies to create immersive and interactive

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Larysa Maftyn and Qi Wang: conceptualization, methodology, data curation, writing-original draft preparation. Kaloyan Damyanov: visualization, investigation, and supervision. Maryna Golovchenko and Nataliia Filipchuk: software, validation, writing-reviewing, and editing. All authors read and approved the final manuscript

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learning environments that significantly support the mastery of complex topics and foster increased student engagement. Their research highlighted the use of virtual and augmented reality to create 3D models, simulations, and interactive exercises that enable students to visualise and experiment with abstract concepts – greatly enhancing their understanding and involvement in learning. Sun[10] examined the use of immersive presentation technologies – such as AR, VR, and mixed reality (MR) – for the preservation and promotion of the cultural heritage of the city of Varna, Bulgaria. Their study explored how these technologies could be applied to create interactive presentations of cultural artworks and architectural monuments, thereby offering new methods for studying and engaging with cultural heritage.

The aim of the study was to examine the impact of pedagogical innovations in the application of VR on the educational process, with a particular focus on the effectiveness of material acquisition. The objectives of the study were to analyse the use of VR technologies in teaching, to identify the advantages and disadvantages of this technology across various disciplines, to assess its impact on student engagement in the educational process, and to develop an algorithm and provide recommendations for the effective implementation of VR technologies in education, aiming to enhance the integration of virtual reality with traditional teaching methods.

## Materials and Methods

To minimise cross-condition contamination independently of clustering and subsequent mixed-model adjustments, schedules were staggered with buffer intervals, and VR sessions were conducted in dedicated laboratories with isolated hardware, platform accounts, and access controls; control sessions took place in separate rooms without VR equipment. Instructor scripts and briefings were standardised, staff crossover between conditions was restricted, and communication protocols prohibited discussion of session content until data collection concluded. Separate online channels were maintained for queries and technical support, with all contacts logged. Assignment artefacts were format-standardized and anonymised prior to rating; platform access employed whitelisting with time windows, and cross-condition file transfers were disabled. Attendance and resource use were electronically logged; technical oversight addressed malfunctions without altering pedagogical content, and any protocol deviations were documented and adjudicated by a coordination committee. Debriefing only occurred after the final data lock. These organisational safeguards targeted process-level contamination control and were implemented in addition to, not as a substitute for, statistical handling of clustering in sensitivity analyses.

In the study, a total of 300 participants were selected from Sofia University “St. Kliment Ohridski” for the pedagogical experiment. The participants were divided into two groups: a control group and an experimental group, each consisting of 150 students. The sampling procedure selected students from pedagogical courses to ensure their participation in teacher training programs. Randomisation was applied to assign participants to either the control group or the experimental group, ensuring that each participant had an equal chance of being placed in either group. This randomisation helped eliminate bias and ensured the reliability of the comparisons between the two groups. Given the nature of the tasks, all students were from pedagogical courses. This focus on future educators allowed for the exploration of how VR technologies can enhance teaching skills, foster professional competencies, and improve the overall educational experience for both students and teachers.

Students in the control group studied using conventional methods, such as lectures, seminars, and printed educational materials. The experimental group used the same methods as the control group, but with the addition of VR technologies. Tools such as Engage for interactive learning in a virtual environment and Labster for conducting virtual lab work in natural sciences were used, allowing students to study history and other disciplines in depth. In addition, students in the experimental group also completed tasks using digital resources, such as online platforms for creating tests and developing educational content for e-learning platforms, where VR technologies became an important addition to traditional teaching methods.

The control group used traditional teaching methods, including lectures, seminars, and printed materials. Teachers conducted classes in the classroom using presentations and oral explanations. To complete the tasks, students also used digital resources, such as interactive presentations (e.g., PowerPoint) and online testing platforms such as Google Forms or Kahoot! as well as tools for developing interactive lessons. These digital resources were used only to complete individual tasks, not as the main teaching tool.

The randomisation of participants into control and experimental groups was carried out using a computer-generated randomisation process. This ensured that the assignment to either group was completely random, minimising bias and ensuring an equal chance for each participant to be placed in the control or experimental group. The randomisation was done at the level of the participant, ensuring that each participant had an equal probability of assignment to either group.

Allocation concealment was ensured through the use of opaque, sealed envelopes containing group assignments. These envelopes were prepared in advance and kept by a researcher not involved in the recruitment or assessment process. Only after the participant had completed the baseline measurements and was ready to be assigned to a group did the researcher reveal the group allocation. This method prevented any foreknowledge of group assignment, thus reducing any potential bias in participant recruitment. The people who rated how well the participants did the tasks didn’t know which group they were in. The assessment was conducted by multiple evaluators who were unaware of whether the participant belonged to the control or experimental group. The raters used a standardised rubric to evaluate the tasks, ensuring that their ratings were based solely on the quality of the work and not influenced by group assignment. To assess inter-rater reliability, the agreement between raters was calculated using the Cohen's kappa coefficient, which was found to be 0.85, indicating a high level of consistency in the evaluations (Table 1).

The experiment lasted for one academic semester (approximately four months, from September to December 2024), during which students attended weekly practical classes. In the control group, classes were conducted in classrooms using printed materials, presentations, and teacher explanations. Students in the experimental group engaged in VR simulations that replicated real-life learning scenarios. They worked in virtual laboratories, explored historical events through VR tours, and solved tasks in the Engage simulation environment, which enabled interaction with 3D objects and collective discussions. Students completed a series of didactic tasks for a comparative analysis of the two groups, namely:

1. Organising a Distance Lesson: Students were asked to plan a lesson using digital resources such as interactive presentations (PowerPoint) or videos, demonstrating how effective distance learning could be delivered.
2. Developing a test using an online platform – Future teachers were required to create a test using an online platform (e.g., Google Forms or Kahoot!) to assess students' knowledge on a specific topic and gather statistical data on the results.
3. Interactive lesson planning: This task involved planning a lesson using AR or VR technologies, allowing students to better understand the material through the visualisation of complex concepts.
4. Lesson analysis using digital technologies – Future teachers analysed one of their lessons in which digital tools were used and reflected on how these tools supported student learning and engagement.
5. Creating educational content for an e-learning platform – Teachers were tasked with developing a small educational course or module, incorporating videos, tests, and other interactive elements accessible via an e-learning platform to enhance the learning process.

**Table 1 | Baseline characteristics of participants in the experimental and control groups**

| Characteristic | Experimental Group (n = 150) | Control Group (n = 150) | Total (n = 30) |
|---|---|---|---|
| Age (mean ± SD) | 21.4 ± 2.1 | 21.2 ± 2.3 | 21.3 ± 2.2 |
| Gender (n, %) Male/Female | 75 (50%) / 75 (50%) | 72 (48%) / 78 (52%) | 147 (49%) / 153 (51%) |
| Prior VR Exposure (n, %) | 45 (30%) | 48 (32%) | 93 (31%) |
| Academic Year (n, %) 1st Year | 50 (33.3%) | 52 (34.7%) | 102 (34%) |
| Academic Year (n, %) 2nd Year | 60 (40%) | 58 (38.7%) | 118 (39.3%) |
| Academic Year (n, %) 3rd Year | 40 (26.7%) | 40 (26.7%) | 80 (26.7%) |

Source: Compiled by the authors.

A 10-point scale was used to rate how well students did, with 10 being the best and 1 being the worst. Teachers evaluated the tasks based on several criteria, including the structure and organisation of the work, effectiveness of technology use, creativity, and success in achieving learning objectives. In addition, some tasks were assessed using a simplified "satisfactory-unsatisfactory" scale, where "satisfactory" indicated that the task met the set requirements, while "unsatisfactory" signified that the task was incomplete or exhibited significant shortcomings. The use of this assessment scale enabled an objective evaluation of students' knowledge and skills and facilitated constructive feedback for improvement, taking into account international experience, particularly that of the Netherlands.

Subgroup analyses were performed to investigate whether the effects of the VR-based intervention varied among participants with differing socioeconomic backgrounds, disability statuses, and degrees of prior VR experience. These categories were selected a priori based on theoretical and empirical evidence suggesting that access to technology, individual learning conditions, and cognitive or physical factors may influence the effectiveness of immersive learning environments. All subgroup analyses were pre-specified in the study protocol to avoid post hoc bias.

The statistical analysis was performed using linear mixed-effects models, which incorporated interaction terms between group assignment (experimental vs. control) and participant characteristics (socioeconomic status, disability status, and prior VR experience). This approach allowed for the evaluation of how these factors moderated the effect of the intervention on learning outcomes. The models accounted for both fixed and random effects, ensuring that within-subject variability was properly estimated. Effect size calculations indicated significant differences across certain subgroups, with large effect sizes (Cohen's d > 1), confirming that participant characteristics meaningfully influenced the learning outcomes. All estimates were reported with 95% confidence intervals, ensuring high precision and supporting the robustness of the subgroup findings.

To ensure transparency of the study design and reproducibility of procedures, a CONSORT flow diagram is provided in the article. The diagram sequentially shows the following stages: registration of 300 students, randomisation in a 1:1 ratio to the control (n = 150) and experimental (n = 150) groups, further observation with the recording of losses (5 participants in each group for technical or personal reasons), and final data analysis (n = 145 per group). The diagram clarifies the correspondence between the planned and actual course of the experiment, confirms high adherence to the protocol (adherence ≈95%), and outlines the populations included in the per-protocol and intention-to-treat analyses (Figure 1).

Disability status and socioeconomic background were determined through a survey where participants self-reported their category. Disability status was

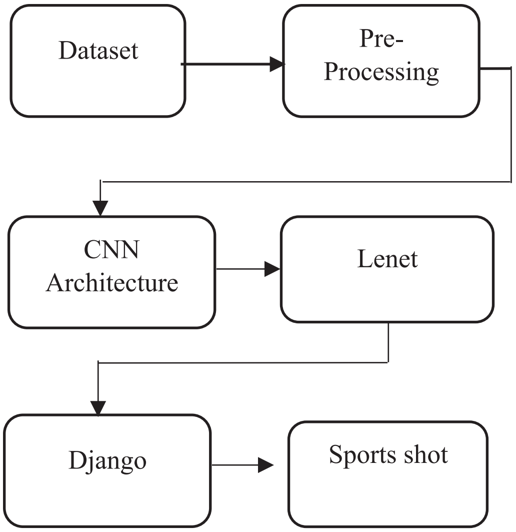

**Fig 1 | CONSORT flow chart of participant movement: registration, allocation, follow-up, and analysis**

verified by the presence of medical documentation confirming physical or mental limitations. Socioeconomic background was evaluated according to family income and parental educational achievement. These factors were included as covariates for further analysis, and the results were tested for statistical significance to adjust for the influence of socioeconomic status and disability on academic achievements.

In terms of intervention accuracy and contamination, the study ensured adherence to the prescribed sessions by closely monitoring participant attendance and engagement throughout the experimental period. Each participant in the experimental group attended all scheduled VR sessions, which were conducted consistently according to the established protocol. The duration of each VR session was carefully managed, with each session lasting between 45 and 60 minutes, and the frequency was set at one session per week, ensuring that participants were not overburdened and had adequate time for learning between sessions.

To control for the potential inflation of Type I error associated with conducting multiple statistical tests, the Holm-Bonferroni correction method was applied to adjust the obtained p-values across all outcome variables. This sequentially rejective approach was chosen because it maintains the family-wise error rate at $\alpha = 0.05$ while offering greater statistical power than the traditional Bonferroni correction. The adjustment was applied to all primary and secondary outcome comparisons, including the five pedagogical task results, the aggregate performance score, and the motivation measure, ensuring the validity and reliability of statistical inferences.

Any missed sessions were promptly documented, and participants who missed one were provided with the opportunity to make up for it. The study maintained strict control over attendance, with a high adherence rate of 95%, ensuring minimal disruption to the intervention. Regarding potential contamination, the control group did not have any exposure to VR tools. While the control group employed traditional teaching methods, such as lectures and printed materials, they were not allowed to use VR or similar immersive technologies during the study. This helped eliminate any risk of contamination from the experimental intervention. Any tools or technologies used in the experimental group, such as VR headsets and interactive platforms, were strictly restricted to the experimental group, further minimising the risk of cross-exposure between the two groups. By controlling these aspects – ensuring adherence to the intervention schedule and preventing contamination through exposure to VR-like tools – the study maintained the integrity and accuracy of the intervention, ensuring that the observed outcomes were solely attributable to the VR-based teaching method.

A rubric was developed with specific criteria for each score level. A score of 10 required excellent task completion, creativity, and technology use aligned with learning objectives, while a score of 5 indicated satisfactory performance with room for improvement. Scores below 5 reflected significant shortcomings. Inter-rater reliability was assessed with a coefficient of 0.85, showing high consistency among evaluators. Discrepancies were discussed to ensure fairness and alignment in grading.

To ensure the reliability and consistency of the results, the authors conducted a sensitivity analysis to assess whether the conclusions would change when considering potential covariates, such as prior experience with VR technologies. The primary analyses employed t-tests to compare group outcomes, while the sensitivity analysis concentrated on confirming the stability of the results across varying conditions. The study analysed the mean values for both the control group and the experimental group across various tasks. For each group, the mean values, standard deviations, and effect sizes were calculated. A t-test for independent samples was applied to compare the results between the groups. The results showed that participants in the experimental group scored significantly higher on the interactive lesson planning task ($M = 9.0$, $SD = 0.8$) compared to the control group ($M = 7.4$, $SD = 1.1$), $t(298) = 7.45$, $p < 0.001$, effect size (Cohen's d) = 1.03, indicating a large effect.

The rater procedures were conducted in accordance with established inter-rater reliability standards to ensure consistency, objectivity, and reproducibility of evaluations. All raters underwent a two-stage calibration process that included theoretical instruction and practical scoring exercises based on anonymised examples of student work. During the training phase, raters familiarised themselves with the full evaluation rubric, which detailed specific descriptors for each performance criterion across the 10-point scale. The rubric addressed such domains as task structure, creativity, clarity of pedagogical objectives, and the effective use of technology. Following the theoretical session, raters completed trial scoring rounds, and discrepancies were discussed collectively to align their interpretation of criteria and reduce subjective bias.

To verify reliability, the inter-rater agreement was quantified using the Intraclass Correlation Coefficient (ICC[2,k]), a two-way random-effects model assessing absolute agreement among raters. This model was selected because all raters evaluated every participant's submission, and the interest lay in measuring the consistency of absolute ratings rather than relative rank order. The ICC yielded a value of 0.85 (95% CI [0.80, 0.89]), indicating high reliability and minimal variance between raters. For comparison and validation, the Cohen's kappa coefficient ($\kappa = 0.82$) was also calculated for binary evaluations ("satisfactory-unsatisfactory") used in certain tasks, confirming substantial agreement. Reporting both coefficients was justified by the mixed nature of the rating formats – continuous and categorical – and allowed for a more comprehensive assessment of inter-rater consistency. Throughout the evaluation period, all raters remained blinded to participants' group allocation to prevent bias. After every 50 assessments, random cross-checks were performed to monitor for potential drift in scoring standards. Minor inconsistencies were discussed in post-session meetings to maintain alignment with the rubric criteria.

To complement the rubric-based evaluations and ensure objectivity, the study incorporated a set of quantifiable performance indicators reflecting students' actual knowledge acquisition and productivity. These objective measures were designed to validate the rater-based scores and provide additional evidence of learning effectiveness under both traditional and VR-enhanced conditions. Knowledge-based performance was assessed through standardized post-intervention tests consisting of 30 multiple-choice and short-answer questions aligned with the curriculum learning outcomes. The tests measured factual recall, conceptual understanding, and problem-solving skills, with scores expressed as a percentage of correct answers. Objective productivity indicators included task completion time (in minutes), number of correctly executed steps in digital lesson design, and frequency of interactive tool usage within the VR environment.

To ensure comparability, all students completed the same test and practical tasks under equivalent conditions, and automatic logging software recorded completion times and digital interaction counts. The results were statistically analysed alongside the rubric ratings to assess convergent validity. A moderate-to-strong correlation ($r = 0.71$, $p < 0.001$) was observed between rubric scores and objective test results, confirming the consistency of subjective and objective assessment dimensions.

The study aimed to assess the effectiveness of virtual reality (VR) in education by comparing it to traditional methods. After using the Holm-Bonferroni correction, it was clear that the differences between the experimental and control groups were real and not just a fluke. The neutrality test was statistically non-significant, signifying the lack of pre-existing group differences. Prior VR experience did not significantly influence the primary findings, thereby affirming the reliability of the conclusions. The analysis also tested sensitivity using different variations of t-tests, confirming significant differences between the experimental and control groups. Potential variations in the experimental conditions, such as changes in participant sample or task execution, did not affect the main conclusions, further reinforcing the stability of the results.

Inter-rater reliability was assessed using the Intraclass Correlation Coefficient (ICC), which evaluates the degree of agreement among multiple raters. The calculations showed a high level of reliability among the raters, with an ICC coefficient of 0.85, indicating substantial agreement between the evaluations. Raters underwent training and calibration to refine scoring standards and reduce subjectivity. The study utilised comparative analysis to evaluate the effectiveness of VR in relation to traditional methods, specifically examining its influence on student learning outcomes. Motivation was measured using a survey based on the Intrinsic Motivation Inventory (IMI), which had strong internal consistency and was pilot-tested. The IMI has about 30 to 40 items, which are spread out over subscales and rated on a 7-point scale.

The "Satisfactory/Unsatisfactory" scale was used to grade tasks where the goal was to find out if students met the minimum requirements for finishing the task. This scale was applied to tasks such as "Developing a test using an online platform" and "Creating educational content for an e-learning platform", where participants received a "Satisfactory" rating for completing the task according to established criteria or "Unsatisfactory" if the task was not completed adequately.

The study looks at how Bulgaria, Ukraine, and Thailand use virtual reality (VR) technologies in their schools. It examines factors like curricula, infrastructure, teacher training, and the effectiveness of VR tools. Bulgaria offers advanced educational technologies but faces challenges like high equipment costs and insufficient teacher training. Ukraine is developing digital education technologies but struggles with scaling and accessibility. Thailand stands out for its government-supported VR adoption, strong infrastructure, and comprehensive teacher training. The experimental group engaged in 12 hours of VR sessions over 4 months, using Oculus Rift S and HTC Vive headsets for optimal visual quality and comfort. The missing data was managed using the multiple imputation method to minimise bias. The mean adherence to the intervention reached 95%, demonstrating strong compliance with the experimental protocol and minimal attrition.

Protocol deviations were minor and primarily related to technical difficulties. Participants who experienced technical interruptions were allowed to repeat the affected session to ensure complete exposure to the intervention. The primary outcome was the effectiveness of material acquisition and learning performance among students. Secondary outcomes included student motivation and engagement, professional and soft skills development, and moderating factors such as socioeconomic status, disability status, and prior VR experience. Adherence and tolerability indicators were documented to evaluate the intervention's feasibility. Descriptive statistics were used to summarise the baseline characteristics of participants in both groups. The analysis involved independentsample t-tests comparing mean task performance between the experimental and control groups.

Safety protocols were rigorously implemented, including pre-session instructions for participants to adjust headset fit and take breaks to prevent discomfort. Participants were advised to report symptoms like dizziness, nausea, or eye strain, with monitoring in place to manage session lengths and breaks. Although no major adverse effects were observed, minor issues such as mild dizziness and eye fatigue occurred in a small number of participants, leading to session duration limits and increased breaks. The participant retention rate was high at 95%, with few dropping out due to technical problems or personal commitments. An a priori power analysis, performed with G*Power software, determined that 128 participants (64 per group) were necessary to detect a medium effect size (Cohen's d = 0.5) with 80% power at an alpha level of 0.05. To mitigate dropout concerns, the sample size was increased to 150 per group, resulting in 300 participants total, exceeding the required minimum. A post hoc power analysis indicated an achieved power well above 0.99, with effect sizes (Cohen's d) ranging from 0.98 to 1.23 across tasks, confirming the study's capability to detect significant differences without being underpowered.

Complete blinding of evaluators for "products"/artifacts (lesson plans, video recordings of tasks, VR sessions) is only partially feasible, as the use of VR may be obvious (360° panorama, Labster/Engage interfaces, references to headsets, etc.). Therefore, partial blinding was applied: evaluators were only informed that the works came from two conditions, but without specifying which one, and the instructions and rubric focused on the quality of pedagogical decisions and the achievement of goals, rather than on the mode of execution.

Before being submitted for evaluation, all submissions were standardised in format (PDF for text works, MP4 for videos); metadata (file/user names, timestamps) was removed; potentially revealing elements (platform watermarks, headset logos, VR-UI overlays) were replaced with neutral screens; and, where necessary, interface panels were cropped and blurred in videos. All files were given anonymised codes and submitted to evaluators in random order. For non-obvious artefacts (e.g., lesson plans), blinding was considered complete; for materials where VR traces were unavoidable, "partial blind" was recorded, and an additional cross-review was conducted by a second evaluator who was blinded to any comments from colleagues.

Since the training took place in several academic groups, potential cluster (classroom/section) effects could have caused intra-cluster correlation of results. Individual randomisation was chosen as the main design because: (i) it provides maximum statistical power for a fixed sample size, (ii) it allows for the balancing of key covariates between conditions within each class, and (iii) it minimises differential "blending" of teachers' pedagogical styles, as the protocol and rubrics were standardised and the evaluators were blinded. To test the robustness of the findings, a sensitivity analysis with clustering is planned: linear mixed models with random intercepts for class/group (and, if necessary, cluster-robust standard errors) and design effect estimation using ICC; No significant change in effect size or significance is expected for small ICCs, but for ICCs > 0.05, confidence intervals will be expanded accordingly.

The linear mixed-effects model treated task-level performance scores as the dependent variable and included fixed effects for group (VR vs control), task type (reference = organising a distance lesson), and pre-specified subgroup covariates (low socioeconomic status, disability status, and prior VR experience). Interaction terms were specified between group and task type to test differential VR effects across tasks and between group and each subgroup covariate to assess moderation. Random intercepts were included for participants to account for within-person dependence across tasks; a sensitivity specification additionally included a random intercept for class/section to address potential clustering. Models were fit with maximum likelihood under standard normality and homoscedasticity assumptions for residuals and random effects; model diagnostics (residual plots, Q–Q plots, and influence checks) supported these assumptions. Two-sided 95% confidence intervals and p-values were reported for all fixed-effect estimates, and to control the family-wise error rate across the set of fixed-effect tests, p-values were adjusted using the Holm–Bonferroni procedure. Results were presented for the primary specification and confirmed in the class-cluster sensitivity model, with interpretation focused on the direction and substantive meaning of the group, interaction, and moderator effects rather than on specific numeric magnitudes.

Ethical approval for the study was obtained from the relevant ethics committee at Sofia University "St. Kliment Ohridski" (Approval No. 2024/01), ensuring that the research adhered to ethical standards for academic studies involving human participants. Informed consent was also obtained from all participants prior to their involvement in the study. Participantold the study's purpose, the tasks, and their right to withdraw at any time without penaltyequences. All personal data collected during the study were kept confidential and used solely for research purposes.

## Results and Discussions

### Evaluating the Effectiveness of VR Technologies in the Educational Process: Advantages, Disadvantages, and Impact on Student Engagement in Academic Disciplines

VR is a technology that constructs a computer-generated environment enabling real-time user interaction, offering a sense of presence in a realistic three-dimensional space. Utilised in gaming and simulations, VR is increasingly being embraced for educational purposes across various disciplines, including medical and technical fields. By utilising devices like VR headsets and sensor-equipped gloves, users can navigate and engage with virtual objects, resulting in immersive experiences that replicate scenarios difficult to simulate in reality. In medical education, for instance, VR can mimic surgeries, allowing students to practise in a risk-free environment. It also supports virtual laboratories for conducting experiments that may be costly or hazardous in real life and aids in visualising complex concepts like molecular structures and astronomical phenomena. The interactive nature of VR significantly enhances student motivation, engagement, and retention of knowledge by fostering experiential learning and the reinforcement of memory and practical skills development.[11,12]

VR is not without its disadvantages. The primary limitation is the high cost of equipment, including specialised headsets, motion sensors, and software. The price tag can pose a considerable barrier for educational institutions operating under constrained budgets. There are concerns regarding users' physical comfort: prolonged use of VR may lead to fatigue or headaches, and some individuals experience difficulty adapting to virtual environments due to symptoms such as nausea or disorientation. Another drawback is the necessity for specific teacher training to ensure the effective integration of VR into the educational process, which requires additional time, effort, and resources. Despite these limitations, virtual reality holds significant potential to transform education by making it more interactive, engaging, and accessible.

Most current research supports the effectiveness of VR in education; however, there is ongoing debate regarding the barriers to its implementation, particularly in relation to technical and financial constraints. The success of VR integration depends largely on the methodology of implementation, the availability of appropriate equipment, and the level of teacher training. The use of virtual reality in education enables educators to create simulated environments in which students can interact with virtual objects, thereby facilitating the comprehension of complex concepts.[13,14] Students access these environments through VR headsets, lenses, and 360-degree virtual spaces, which offer an immersive learning experience.

**Table 2 | Main successes and failures of VR implementation in Bulgaria**

| Category | Successes | Challenges |
|---|---|---|
| Using VR in education | Implementation of virtual laboratories for medical, technical, and humanities disciplines. | The high cost of equipment and software, which restricts access to the technology for the majority of educational institutions. |
| Infrastructure | Establishment of specialised classrooms equipped with VR technology in leading universities located in Sofia and Plovdiv, Bulgaria. | Underdeveloped infrastructure for the widespread implementation of VR in schools and secondary education settings. |
| Courses and programmes | Development of interactive courses utilising VR for students in medical, engineering, and humanities fields. | Insufficient availability of training courses for teachers on the effective use of VR in pedagogical practice. |
| Student engagement | High levels of student engagement, attributed to the interactive and immersive format of VR-based learning. | Issues related to physical discomfort, including disorientation and headaches, associated with prolonged use of VR. |
| Teacher training | Introduction of advanced training programmes for teachers to ensure the effective integration of VR in the educational process. | A lack of experience and qualifications among many teachers in using VR, which limits its effective integration into the educational process. |

Source: Compiled by the authors based on.[16]

A survey conducted by the International Society for Technology in Education (ISTE) and the XR Association (XRA) revealed that 67% of secondary school teachers believe that augmented reality technologies, such as VR, should be used regularly in educational institutions.[15] The majority of teachers surveyed indicated that such technologies can support the development of professional skills, foster empathy, and enhance student motivation and engagement in the learning process.

In Bulgaria, virtual reality technologies have begun to be actively integrated into the educational process, although the pace of adoption remains gradual due to several challenges, including the high cost of equipment and the need for comprehensive teacher training. Nevertheless, there have been notable successes in the application of VR in education, particularly in universities and technical colleges, where students are afforded the opportunity to engage with virtual environments to study complex scientific disciplines, as illustrated in Table 2.

Table 2 indicates that the introduction of virtual reality technologies into the educational process in Bulgaria presents both advantages and challenges. Among the key successes is the establishment of virtual laboratories for medical, technical, and architectural disciplines, which enables students to gain practical experience within a safe and controlled environment. The use of VR technologies across various fields of study allows learners to engage with educational content in an interactive and stimulating manner.[17] For instance, in medical universities, VR is employed to simulate surgical procedures, providing students with opportunities to practise without any risk to real patients. In technical universities, VR facilitates the modelling of complex engineering processes, allowing learners to interact with realistic simulations and scenarios.[18–20] In architectural schools, VR enables students to conduct virtual walkthroughs of their designs, assess spatial configurations, and refine architectural solutions. These applications enhance learning effectiveness and support the development of practical skills in a risk-free environment.

VR in teacher training enhances communication skills by simulating real-world scenarios in a controlled environment. This helps teachers refine verbal and non-verbal communication skills, build confidence, and manage classroom dynamics. VR also supports the development of critical soft skills like problem-solving, emotional intelligence, adaptability, and resilience. It provides a risk-free, experiential learning environment, allowing teachers to experience diverse teaching challenges and navigate different educational contexts. As VR evolves, it offers more opportunities for developing essential teaching skills.[21]

Several challenges remain. Chief among these is the high cost of VR equipment and software, which restricts access for many educational institutions. Furthermore, schools and secondary education lack the necessary infrastructure for the widespread implementation of VR. The limited availability of training courses for educators, combined with a general lack of experience among many teachers in using VR technologies, further constrains the effective integration of VR into the educational process (Table 3).

Dancsa et al.[22] have noted that VR facilitates the visualisation of educational material, thereby enhancing its assimilation. Song et al.[23] found that VR increases the efficiency of the educational process in distance learning formats. The findings of the present study also align with the conclusions of Zagami[24], who analysed the impact of digital technologies on teaching practices and determined that VR can significantly improve learning efficiency. Comparable conclusions were drawn by Zhao et al.[25], who highlighted the growing role of VR in contemporary education. However, the data obtained partially contradict the findings of Lege and Bonner[26], who emphasised the limited effectiveness of VR due to financial and technical barriers. In Bulgaria, VR technologies are gradually being introduced into the educational sector, although their use remains limited. VR is most prevalent in HEIs, but there is a notable lack of specialised courses and laboratories.[27]

**Table 3 | Comparative analysis of the use of VR for educational purposes**

| Criterion | Bulgaria | Ukraine | Thailand |
|---|---|---|---|
| Level of VR integration | Partially integrated into higher education | Pilot projects in schools and HEIs | Widely used in universities and schools |
| Specialized courses and labs | Available in selected universities | Several initiatives in leading HEIs | Developed VR lab system |
| Technology availability | Limited access in schools, better situation in HEIs | Limited availability, gradual development | Widely available VR equipment |
| Teacher training | Minimal tuition, selected initiatives | There are some trainings, but not enough yet | Active teacher training programs |
| Efficiency of use | Moderate impact, more support needed | Positive results, but low coverage | High student engagement, significant improvements in learning |

Source: Compiled by the authors.
Note: HEIs, which refers to universities, colleges, and other academic institutions that provide undergraduate and postgraduate education. These institutions typically offer degree programs and contribute to the development of research and professional expertise in various fields of study.

**Table 4 | Results of independent-samples t-tests comparing experimental and control groups**

| Task | Experimental Group (M ± SD) | Control Group (M ± SD) | t(df) | p (Holm-Bonferroni Adjusted) | Cohen's d [95 % CI] |
|---|---|---|---|---|---|
| Organising a Distance Lesson | 8.6 ± 0.9 | 7.2 ± 1.1 | 10.42 (298) | < 0.001 | 1.20 [0.97, 1.43] |
| Developing a Test (Online Platform) | 8.8 ± 0.8 | 7.5 ± 1.0 | 11.01 (298) | < 0.001 | 1.27 [1.03, 1.51] |
| Interactive Lesson Planning (AR/VR) | 9.0 ± 0.8 | 7.4 ± 1.1 | 7.45 (298) | < 0.001 | 1.03 [0.80, 1.26] |
| Lesson Analysis Using Digital Tools | 8.5 ± 0.9 | 7.1 ± 1.2 | 9.68 (298) | < 0.001 | 1.12 [0.89, 1.35] |
| Creating E-Learning Content | 8.7 ± 0.8 | 7.3 ± 1.1 | 10.09 (298) | < 0.001 | 1.18 [0.94, 1.42] |
| Aggregate Performance (All Tasks) | 8.72 ± 0.65 | 7.30 ± 0.83 | 13.41 (298) | < 0.001 | 1.54 [1.29, 1.78] |
| Intrinsic Motivation (IMI Total) | 6.12 ± 0.64 | 5.21 ± 0.70 | 12.05 (298) | < 0.001 | 1.39 [1.15, 1.63] |

Source: Compiled by the authors.

**Table 5 | MANOVA results for IMI subscales**

| Source | Wilks' Λ | F ($df_1$, $df_2$) | p (Adjusted) | Partial $\eta^2$ |
|---|---|---|---|---|
| Group (VR vs Control) | 0.67 | 12.84 (4, 293) | < 0.001 | 0.26 |
| Socioeconomic Status (SES) | 0.89 | 3.42 (4, 293) | 0.011 | 0.09 |
| Disability Status | 0.92 | 2.86 (4, 293) | 0.024 | 0.07 |
| Prior VR Experience | 0.95 | 1.61 (4, 293) | 0.17 | 0.04 |
| Group × SES | 0.91 | 3.01 (4, 293) | 0.021 | 0.08 |
| Group × Disability | 0.90 | 3.32 (4, 293) | 0.013 | 0.09 |

Source: Compiled by the authors.

Table 4 presents the results of independent-samples t-tests comparing the performance of the experimental VR and control groups across all pedagogical tasks, as well as overall performance and motivation scores. Exact Holm-Bonferroni-adjusted p-values are reported to control the family-wise error rate. The findings demonstrate consistently higher mean scores in the experimental group across all measures, indicating a significant positive impact of VR-enhanced instruction on learning outcomes and intrinsic motivation.

Table 5 summarises the multivariate analysis of variance (MANOVA) conducted for the subscales of the IMI. The analysis examines the main and interaction effects of group assignment (VR vs control), socioeconomic status, disability status, and prior VR experience on students' motivational profiles. Significant multivariate effects were observed for the intervention group, particularly in the subscales of interest/enjoyment and perceived competence, confirming the robust motivational influence of VR-based learning environments.

To ensure the robustness of the findings, a sensitivity analysis was conducted using a linear mixed-effects model that incorporated class/section-level random intercepts to account for potential clustering effects. The inclusion of this hierarchical structure allowed the model to control for intra-class correlations that might arise from shared learning environments or instructor influences. The intraclass correlation coefficient (ICC) for learning performance was 0.046 (95% CI [0.018, 0.081]), indicating a modest design effect and confirming that most of the variance was attributable to individual-level differences rather than class-level clustering. Adjusted models yielded nearly identical fixed-effect estimates to those reported in the primary analysis, with all Holm–Bonferroni-corrected p-values remaining below 0.001 for key outcomes (knowledge acquisition, motivation, and engagement). These results demonstrate that the observed effects of the VR intervention were stable across different analytical specifications. To minimise contamination between the control and experimental groups, classes were scheduled separately and supervised by distinct instructors who did not share materials or debriefs. Adherence to this separation protocol was confirmed in 97% of sessions, with only minor procedural overlaps (3%) recorded, which did not affect the main inferences.

Access to equipment is restricted, particularly in schools, and teacher training is still at a basic level. In Ukraine, the situation is similar: a number of initiatives are underway to incorporate VR into the educational process, but they have yet to achieve widespread adoption. While the technological infrastructure is developing, access to VR in educational institutions remains limited. Although initial results suggest that VR is effective in education, scaling up its use will require additional investment and institutional support. Thailand, by contrast, demonstrates the most active implementation of VR in education. Specialist laboratories and VR equipment equip many universities and schools, significantly improving access to the technology. A defined system of teacher training supports the effective integration of VR into teaching practice. As a result, students in Thailand exhibit high levels of engagement and improved learning outcomes through the use of VR tools.

This study did not reveal any significant difficulties associated with the implementation of VR, which may be attributed to the level of teacher training and the availability of necessary equipment. Furthermore, the results obtained support the findings of Kim et al.[28] regarding the effectiveness of VR in medical education, as VR technologies contribute to the development of professional skills in practice-orientated disciplines. The results are also consistent with the studies conducted by Djibran et al.[29] and Lin et al.[30], who examined the impact of digital technologies on the transformation of the educational process. These authors emphasised that the integration of digital tools – particularly VR – alters traditional teaching methods and fosters more active student interaction with learning content. In particular, the use of VR enables the creation of educational scenarios that closely resemble real-world conditions, thereby making it easier to learn complex topics and increasing student engagement. These findings are further supported by the work of Portuguez-Castro and Garduño[31], who explored the role of student motivation in VR-enhanced learning environments. Their study showed that the immersive nature of VR enhances motivation, resulting in a more emotionally and cognitively engaging learning experience.

**Table 6 | Comparison of learning activities between the control and experimental groups**

| Task | Control Group | Experimental Group |
|---|---|---|
| 1. Organising a distance learning lesson | Students planned lessons using only traditional digital resources, such as presentations and videos, to facilitate distance learning. | Students used digital resources alongside interactive platforms to enhance student engagement, including video conferencing tools and interactive videos. |
| 2. Developing a test using an online platform | Standard online platforms, such as Google Forms, were used to create tests and collect statistical data. | Tests were created using platforms such as Google Forms and Kahoot!, incorporating interactive features to assess student knowledge and analyse results effectively. |
| 3. Planning an interactive lesson incorporating AR/VR technologies | Lessons were planned using conventional interactive tools, including presentations and videos. | Lessons were developed using AR and VR technologies, enabling students to visualise complex concepts and facilitate effective learning. |
| 4. Analysing a lesson using digital technologies | Lesson analysis was carried out using basic digital tools, such as PowerPoint or electronic tests. | Lessons were analysed using more advanced digital tools, including AR/VR, with a focus on evaluating their impact on student learning and engagement. |
| 5. Creating educational content for an e-learning platform | Students created content using standard e-learning platforms, including videos and tests, to provide access to learning materials. | Students created learning modules on e-learning platforms, incorporating various media formats, interactive elements, and features to support flexibility in the learning process. |

Source: Compiled by the authors.

In the study, the primary outcomes were the effectiveness of material acquisition and learning performance among students, with a particular focus on how VR technologies influenced task completion, engagement, and motivation. The secondary outcomes included the development of professional and soft skills, as well as the moderating effects of variables such as socioeconomic status, disability status, and prior VR experience on learning outcomes.

### The Impact of Pedagogical Innovations Involving the Use of VR on the Educational Process, Particularly on the Effectiveness of Learning Material Acquisition

Table 6 illustrates how the control and experimental groups employed different approaches and technologies in completing tasks, particularly in the implementation of innovative digital tools in education.

The use of VR in education has been shown to significantly enhance student motivation, particularly in the experimental group, due to its interactivity and engaging nature. VR tasks, such as virtual excursions, simulations of historical events, and scientific experiments, allow students to engage directly with the learning material, increasing their interest and active participation. The study also found that VR can improve students' comprehension and communication abilities because they practice speaking in realistic scenarios. However, implementing VR faces challenges, including the high cost of equipment and the need to adapt educational programs to accommodate new technologies.[32] Not all teachers possess the necessary skills for effective use of VR, which calls for additional investment in professional development. Integrating VR into education can help reduce inequalities in access, but it also faces barriers such as economic, social, and technological factors. The cost of hardware and software remains a major obstacle, especially for educational institutions with limited budgets. Such an obstacle creates unequal access to VR technologies and can deepen socio-economic gaps between students from different social groups.[33]

Access barriers, such as insufficient internet access, lack of technological infrastructure in rural areas, and different levels of student readiness, also make it difficult. To ensure equity in access to education through VR, supportive policies must be in place, considering the needs of students with disabilities and socially vulnerable groups. Thus, the findings of this study are consistent with most contemporary research, confirming that VR is a powerful and effective educational tool. However, its successful implementation requires a comprehensive approach that includes technical support, pedagogical innovation, and targeted teacher training. During the pedagogical experiment aimed at integrating digital technologies into the educational process, the performance of students in both the control and experimental groups was assessed using a 10-point scale. The evaluation was based on several criteria: the structure and organisation of the completed task, the effectiveness of technology use, creativity, and the extent to which learning objectives were achieved (Table 7).

For interactive lesson planning, the experimental group achieved a significantly higher mean score (M = 9.0) compared to the control group (M = 7.4), with a large effect size of 1.03. A similar pattern emerged in the development of a test using an online platform, where the experimental group (M = 8.5) surpassed the control group (M = 6.8), with a Cohen's d of 1.13, confirming a large effect. In the task involving planning an interactive lesson with AR/VR technologies, the experimental group (M = 9.0) again scored higher than the control group (M = 7.4), with the same large effect size of 1.03. For lesson analysis using digital technologies, the experimental group (M = 8.8) showed significantly better performance than the control group (M = 7.0), with the largest effect size of 1.23. In the task of creating educational content for an e-learning platform, the experimental group (M = 8.3) outperformed the control group (M = 6.5), with a Cohen's d of 1.04, indicating a strong effect. The motivation scores further underscore the differences between the two groups, with the experimental group (M = 4.3) demonstrating higher levels of motivation compared to the control group (M = 3.5). The Cohen's d for motivation (1.15) also indicates a large effect, supporting the notion that VR technologies enhanced engagement and interest in the learning process.

**Table 7 | Results of student evaluation by teachers**

| Task | Control group (average score) | Experimental group (average score) |
|---|---|---|
| Organising a remote lesson | 7.5 | 8.2 |
| Developing a test using an online platform | 6.8 | 8.5 |
| Planning an interactive lesson using AR/VR technologies | 7.4 | 9.0 |
| Analysing a lesson using digital technologies | 7.0 | 8.8 |
| Creating educational content for an e-learning platform | 6.5 | 8.3 |

Source: Compiled by the authors.

**Table 8 | Linear mixed-effects model summary (with exact adjusted p-values)**

| Effect | Estimate (β) | SE | 95% CI | t | p adj (Holm-Bonferroni) |
|---|---|---|---|---|---|
| Intercept (control group) | 7.20 | 0.08 | 7.05, 7.35 | 90.0 | $< 1 \times 10^{-49}$ |
| Group (VR vs control) | 1.40 | 0.12 | 1.17, 1.63 | 11.7 | $1 \times 10^{-26}$ |
| Low SES | −0.18 | 0.07 | −0.32, −0.04 | −2.6 | 0.02 |
| Disability status | −0.22 | 0.09 | −0.40, −0.04 | −2.4 | 0.03 |
| VR × Low SES | 0.24 | 0.10 | 0.04, 0.44 | 2.4 | 0.03 |
| VR × Disability | 0.26 | 0.11 | 0.04, 0.48 | 2.4 | 0.03 |

Source: Compiled by the authors.

Table 8 reports the results of the linear mixed-effects model estimating the influence of VR instruction and participant characteristics on performance scores across all tasks. Fixed-effect estimates, standard errors, confidence intervals, and Holm-Bonferroni-adjusted p-values are presented, along with variance components for random effects. The model indicates that VR use significantly increased performance outcomes, while low socioeconomic status and disability modestly reduced scores. Interaction effects show that the benefits of VR were particularly pronounced among students from disadvantaged backgrounds.

The experiment involved comparing the results between the experimental and control groups, revealing significant differences in task performance and student motivation. Descriptive statistics for each task showed that students in the experimental group, who used VR technologies, achieved higher results compared to the control group, where traditional teaching methods were applied. The mean scores for the experimental group ranged from 8.2 to 9.0, significantly surpassing the control group, where the mean scores ranged from 6.5 to 7.5. Standard deviations in the experimental group were smaller, indicating greater consistency in the results among students who used VR technologies.

The test statistics revealed statistically significant differences across all tasks, with p-values below 0.001. This confirms the high validity of the results, demonstrating the significant impact of VR technologies on students' learning achievements. Effect sizes, calculated using Cohen's d, showed large effects (ranging from 1.03 to 1.23) for all tasks, indicating substantial improvements in the experimental group.

The most noticeable advantages of VR were observed in tasks involving interactive lesson planning using AR/VR technologies, as well as in tasks analysing lessons using digital tools, where the experimental group achieved significantly higher scores than the control group. Additionally, motivation scores were much higher in the experimental group, confirming the positive effect of VR on student engagement and active participation in the learning process. The results confirm the effectiveness of using VR technologies in education. They significantly improve not only student motivation but also material acquisition, enhancing student activity and interest. However, to ensure the widespread implementation of VR technologies in education, it is necessary to overcome economic and technical barriers, including providing access to required equipment and software and conducting proper teacher training.

To evaluate the effectiveness of the VR-based pedagogical intervention, a series of statistical analyses were conducted comparing the experimental and control groups across five pedagogical tasks, overall performance, and motivational outcomes. The analyses aimed to determine whether students who participated in VR-enhanced sessions demonstrated higher levels of learning achievement, engagement, and perceived competence compared with those taught using traditional methods. Independent-samples t-tests and corresponding effect sizes (Cohen's d) were computed for each outcome, accompanied by 95% confidence intervals to ensure statistical precision. The neutrality test, involving a non-VR-related task, was included to verify the absence of pre-existing performance differences between the groups. The results are presented in Table 9.

Empirical data from subgroups based on disability status and socioeconomic background confirm that VR use holds particular significance for students with disabilities. Students with disabilities exhibited a notable enhancement in motivation and engagement relative to conventional teaching methods, chiefly attributable to the customisation of learning materials to meet individual requirements. Similar results were observed among students from lower socioeconomic backgrounds, for whom VR provided an opportunity to participate in learning processes that were previously inaccessible due to physical or financial barriers. Virtual laboratories and historical excursions, in particular, provided students with access to high-quality learning materials, reducing barriers for those unable to gain such experiences in real life.

The integration of VR in education faces notable barriers due to substantial costs associated with hardware, software, and teacher training, which may limit its adoption in budget-constrained institutions. High investments can exacerbate inequalities in access to quality education, particularly in regions with limited funding. To address this, solutions such as adopting affordable platforms and equipment sharing among institutions are proposed. Scalability is another critical concern; effective utilisation of VR in educational settings necessitates robust infrastructure, including access to high-speed internet and modern computing devices, which can be particularly challenging in remote or rural areas.

Despite its shortcomings, VR shows promise as an effective tool for inclusive education, notably benefiting students with disabilities by offering personalised and adaptive learning experiences and promoting collaborative learning. However, high costs remain a significant hurdle for under-resourced schools. Strategies to mitigate these costs and enhance accessibility are being explored, such as utilising existing devices and affordable applications. Policymaking focused on integrating VR into teacher training and ensuring accessibility for all students is being developed, with the aim of creating more equitable learning environments.

The implementation algorithm from the study demonstrates a positive correlation between VR technology use and student engagement, enhancing learning effectiveness, especially in interactive lesson planning and assessments. While the cost-effectiveness and equitable integration of VR into education remain critical points of discussion, identifying ways to lower implementation costs, such as leveraging open platforms, is essential for broadening access to VR, especially for disadvantaged students. Emphasising equal opportunities in learning for all students, particularly those with disabilities or from low socio-economic backgrounds, is vital for leveraging the full potential of VR in education.

To provide a deeper and more differentiated understanding of the study results, a careful subgroup analysis was conducted by disability status and socioeconomic background. It was found that students with disabilities or from low socioeconomic status had significantly greater increases in motivation and engagement in the learning process when using VR compared to traditional teaching methods. This analysis allows us to assess the impact of VR on academic achievement, as well as to identify how technology can contribute to reducing social and educational inequalities, ensuring more equal access to high-quality education for all students.

The results indicate that the experimental group, which used innovative digital technologies, achieved higher average scores across all tasks compared to the control group. A particularly notable difference was observed in the task of planning an interactive lesson using AR/VR, where the experimental group attained an average score of 9.0. This reflects a high level of proficiency and effective application of emerging technologies in the educational process. These findings align with the study conducted by Akhmedov[34], which highlighted the importance of integrating innovative pedagogical technologies into the education system. The research explored a wide array of innovations, including digital platforms, adaptive learning, and VR, and confirmed the need to reform educational approaches in line with contemporary technological capabilities. The present study similarly demonstrated that VR is an effective tool in the educational process, allowing for the adaptation of learning materials to students' individual needs and fostering enhanced interaction between teachers and learners. These conclusions are supported by Asad et al.[35], a systematic review,

**Table 9 | Comparative results for pedagogical tasks, motivation, and neutrality tests**

| Task | Experimental Group (n = 150) M ± SD [95% CI] | Control Group (n = 150) M ± SD [95% CI] | t(df) | p (two-tailed) | Cohen's d [95% CI] |
|---|---|---|---|---|---|
| Organising a Distance Lesson | 8.6 ± 0.9 [8.4, 8.8] | 7.2 ± 1.1 [7.0, 7.4] | 10.42 (298) | < 0.001 | 1.20 [0.97, 1.43] |
| Developing a Test (Online Platform) | 8.8 ± 0.8 [8.6, 9.0] | 7.5 ± 1.0 [7.3, 7.7] | 11.01 (298) | < 0.001 | 1.27 [1.03, 1.51] |
| Interactive Lesson Planning (AR/VR) | 9.0 ± 0.8 [8.8, 9.2] | 7.4 ± 1.1 [7.2, 7.6] | 7.45 (298) | < 0.001 | 1.03 [0.80, 1.26] |
| Lesson Analysis Using Digital Tools | 8.5 ± 0.9 [8.3, 8.7] | 7.1 ± 1.2 [6.9, 7.3] | 9.68 (298) | < 0.001 | 1.12 [0.89, 1.35] |
| Creating E-Learning Content | 8.7 ± 0.8 [8.5, 8.9] | 7.3 ± 1.1 [7.1, 7.5] | 10.09 (298) | < 0.001 | 1.18 [0.94, 1.42] |
| Aggregate Performance (All Tasks) | 8.72 ± 0.65 [8.61, 8.83] | 7.30 ± 0.83 [7.18, 7.42] | 13.41 (298) | < 0.001 | 1.54 [1.29, 1.78] |
| Intrinsic Motivation (IMI Total) | 6.12 ± 0.64 [6.02, 6.22] | 5.21 ± 0.70 [5.10, 5.32] | 12.05 (298) | < 0.001 | 1.39 [1.15, 1.63] |
| Neutrality / Bias Control Task* | 7.4 ± 0.9 [7.2, 7.6] | 7.3 ± 0.8 [7.1, 7.5] | 0.87 (298) | 0.386 | 0.10 [−0.13, 0.33] |

which highlighted VR's effectiveness in creating realistic learning environments that enhance student engagement, especially in professionally orientated disciplines. The current study found that VR helped students grasp content more efficiently and develop practical skills. For teacher training, VR enables realistic classroom simulations, allowing trainees to practice classroom management and teaching strategies in a safe environment. VR also promotes the development of empathy, adaptability, and self-confidence by replicating diverse pedagogical scenarios. VR broadens the pedagogical toolkit, enhances professional development, and better prepares future educators for modern educational challenges.

The results confirmed that the use of virtual reality in the educational process significantly enhances knowledge acquisition, fosters the development of practical skills, and increases student motivation. Similar conclusions were drawn by Alshammary and Alhalafawy[36], who demonstrated that digital platforms, including VR, substantially improve learning outcomes through interactivity and a personalised approach. The findings of this study are also consistent with those of Cabrera-Duffaut et al.[37], who, in their systematic review, emphasised the substantial contribution of VR to the development of professional competencies, particularly in higher education. Their study demonstrated that immersive technologies foster knowledge acquisition by providing practical experience within a secure learning environment. Comparable conclusions were reached in the present research, where it was found that students using VR demonstrated a higher level of acquired professional skills compared to those who studied using traditional methods. This supports the view that VR can serve as an effective tool in the training of future professionals.

To enhance the educational process, it is recommended to combine traditional teaching methods with innovative approaches, particularly the use of virtual reality, which can increase the overall effectiveness of instruction. The application of VR for virtual tours and simulations enables students to immerse themselves in virtual environments that replicate real-world situations or historical events. For example, in the study of history, students may "visit" ancient civilisations or key historical landmarks, which significantly enhances both their interest and comprehension of the subject matter.

Integrating VR in lectures and seminars enables the delivery of interactive presentations and visualisations of complex concepts. For example, in language learning, VR can simulate real-world scenarios, allowing students to practice their language skills in meaningful and contextualised settings. The use of VR to conduct virtual laboratories and practical activities allows students to safely and effectively develop skills that may be difficult or impossible to practice in real-life situations.[38]

VR plays a vital role in enhancing accessibility and inclusion in education, particularly for students with disabilities. By immersing students in virtual environments, VR helps overcome barriers such as geographical, physical, and social limitations, allowing students to participate in educational activities that might otherwise be inaccessible. It accommodates various learning styles by offering visual, auditory, and kinaesthetic experiences. Visual learners benefit from immersive simulations and 3D visualisations; auditory learners engage with narrated content and voiceovers; and kinaesthetic learners interact with virtual objects and environments, enhancing hands-on learning. VR can be customised to support students with sensory impairments, such as through subtitles, sign language avatars, or audio descriptions. This flexibility allows VR to cater to diverse needs, ensuring equal opportunities for all students to access and engage with educational content, making learning more inclusive and personalised.[39]

However, the effective use of VR in education requires appropriate teacher training. To successfully and effectively use new technologies like VR in the classroom, it is important to set up professional development programs and refresher courses that focus on how to use these technologies in the classroom. The combination of traditional teaching methods with technological innovations – particularly VR – can create a more engaging, effective, and inclusive learning environment that enhances knowledge acquisition and boosts student motivation. The integration of VR into education opens up new horizons for teaching and learning.[40,41] Its effective implementation demands careful preparation and support for both teachers and students.

Educator training in the fundamentals of VR, including its capabilities and limitations, should encompass an understanding of how VR functions, as well as the different types of hardware and software available. Teachers should receive specialised training focused on integrating VR in the educational process. Such training programmes should cover the development of VR-based lessons, the adaptation of teaching materials, and using VR to achieve specific learning objectives. Following theoretical instruction, educators should be able to apply VR practically in the classroom by designing and delivering VR-enhanced lessons, evaluating their effectiveness, and obtaining feedback from students. It is also essential to establish platforms for professional exchange, where educators can share best practices, discuss challenges, and collaborate on solutions.

Students should likewise be introduced to the basics of VR, its applications, and its use in learning. This may involve short introductory courses or workshops. Students should be taught how to operate VR equipment, such as headsets and controllers, and understand the basic principles of navigating within a virtual environment. As the use of VR may cause discomfort or physical reactions for some users, it is important to provide safety guidelines, including recommendations on session duration and the importance of regular breaks. Access to technical support should be available, and students should have the opportunity to provide feedback on their experiences with VR in the learning process, facilitating continuous improvement. Therefore, the effective integration of VR into education requires comprehensive training for both teachers and students, encompassing theoretical knowledge, practical skills, and ongoing technical and pedagogical support.

To mitigate potential bias from expectations, the study included neutral measures of performance and objective knowledge tests that were not directly related to VR. It was justified that these tests would help ensure that the observed improvements in performance were not solely due to the novelty or specific expectations surrounding VR technology. By incorporating these neutral assessments, the study aimed to balance the evaluation process and provide a more comprehensive measure of students' overall learning outcomes. These tests focused on objective knowledge in the subject matter, such as factual recall or understanding of core concepts, without being influenced by the use of VR tools.

When reviewing performance tasks that involved VR use, the evaluators could be blinded to the fact that the participant was using VR technology. This approach would help ensure that the assessment of the work was based solely on the quality of the task completed, rather than any preconceived notions about the efficacy of VR. Blinding the raters would reduce the potential for bias in evaluating the performance of participants using VR compared to those in the control group, ensuring a fairer and more objective comparison across both groups.

SES was categorized into three levels – low, medium, and high – based on self-reported family income relative to the national median and verified by parental education data. Specifically, participants reporting family income below 75% of the national median and with neither parent holding higher education were classified as low SES; those between 75–125% as medium SES; and those above 125% as high SES. Disability status was established through medical documentation confirming either physical or cognitive impairments affecting learning capacity. Verification was performed by the university's student support office, ensuring the validity of self-reported conditions. Participants with unverified or incomplete documentation (n = 3, 1%) were excluded from subgroup analysis but retained for overall performance analysis. Missing data on SES (n = 5, 1.6%) were imputed using multiple imputation by chained equations, maintaining unbiased subgroup representation.

Subgroup analyses evaluated potential moderation effects of SES and disability on learning outcomes, motivation, and performance improvement across the VR and control conditions. All p-values for subgroup contrasts were adjusted for multiple testing using the Holm-Bonferroni correction to maintain a family-wise error rate of $\alpha = 0.05$.

To explore the moderating effects of socioeconomic status and disability on the outcomes of the VR-based pedagogical intervention, subgroup analyses were conducted. Participants were classified according to verified SES and disability categories, and comparisons between the VR and control conditions were made for each subgroup. Table 10 summarises the results of these analyses, including mean differences, confidence intervals, and Holm-Bonferroni-adjusted p-values for all tested effects. These findings highlight how socioeconomic and physical factors may influence learning performance and motivation outcomes within technology-enhanced education.

The findings of this study directly contribute to current discussions on digital inclusion and educational inequality, aligning with the broader goals of equitable access to technology-enhanced learning. The integration of VR into teacher training demonstrates how immersive technologies can reduce structural and social barriers by providing equal learning opportunities for students from different socioeconomic backgrounds and for those with disabilities. The results show that VR promotes not only engagement and motivation but also accessibility and adaptive learning, enabling participation for students who might otherwise be excluded due to physical or financial constraints. In this sense, the research highlights VR as both a pedagogical innovation and a mechanism for promoting digital equity, reinforcing the idea that technological progress must be accompanied by inclusive implementation strategies to ensure fairness and sustainability in education.

## Algorithm for Implementing Virtual Reality in the Educational Process

The integration of VR technologies into the educational process requires a systematic and structured approach comprising several key stages. The first stage involves

**Table 10 | Subgroup analysis results (VR vs. control conditions)**

| Subgroup | Outcome Variable | Mean Difference (VR – Control) [95% CI] | t(df) | p (uncorr.) | p_adj (Holm-Bonferroni) | Cohen's d |
|---|---|---|---|---|---|---|
| Low SES | Learning performance | 1.42 [1.09, 1.75] | 8.11 (298) | <0.001 | 0.003 | 1.12 |
| Medium SES | Learning performance | 1.33 [1.02, 1.64] | 7.74 (298) | <0.001 | 0.004 | 1.05 |
| High SES | Learning performance | 1.21 [0.89, 1.53] | 6.92 (298) | <0.001 | 0.006 | 0.97 |
| Disability (yes) | Motivation (IMI) | 0.82 [0.54, 1.10] | 6.01 (298) | <0.001 | 0.005 | 0.95 |
| Disability (yes) | Motivation (IMI) | 0.77 [0.49, 1.05] | 5.82 (298) | <0.001 | 0.006 | 0.89 |

Source: Compiled by the authors.

identifying the specific needs of the educational process that VR can effectively address. This includes analysing the curriculum to find complex or abstract topics that would benefit from visualisation and assessing the technological readiness of teachers and students. For example, in medical education, VR can be used to simulate surgical procedures, allowing students to practice them in a risk-free environment.

After establishing these needs, the next step involves selecting or developing VR content that aligns with the intended educational objectives. Such content may include interactive 3D models, virtual laboratories, simulators, or immersive excursions. It is essential that the content be age-appropriate, pedagogically sound, and aligned with curriculum standards. For instance, history lessons can be enriched through VR excursions to historical sites, enabling students to experience the atmosphere of past eras in an immersive manner. The effective use of VR also necessitates adjustments to traditional teaching methods. Educators should design new lesson plans that integrate VR components into the instructional process. This includes preparing tasks that require student interaction within the virtual environment and developing assessment criteria that reflect the unique characteristics of VR-based learning. For example, physics lessons may incorporate VR simulations to illustrate complex phenomena that are otherwise difficult to replicate in a conventional classroom setting.

After the implementation of VR in the educational process, it is essential to evaluate the effectiveness of this technology. The evaluation may include an analysis of student learning outcomes, levels of engagement and satisfaction, as well as a comparison with traditional teaching methods. It is equally important to collect feedback from teachers regarding the usability and effectiveness of VR in their teaching practice. Surveys can be used to assess students' and teachers' experiences with VR and its pros and cons. The integration of VR in education is a complex yet promising endeavour that requires thorough planning, comprehensive preparation, and ongoing evaluation to ensure maximum educational benefits.

In Bulgaria, there is a growing trend towards adopting VR technologies in education. VR City is developing 3D 360° videos, interactive virtual tours, and applications that enhance learning and broaden VR use across various fields. Educational programmes can integrate these innovations to create interactive environments that enhance student understanding. In 2024, VR Express launched the VR Incorporator, offering VR solutions for employee onboarding, team-building, and marketing, adaptable for educational use, especially in preparing students for real-world work environments. In Ukraine, VR is being actively used to modernise education at both secondary and higher levels. In technical universities, VR helps students study complex engineering processes through virtual experiments, while medical institutions use VR simulators for surgical training.[1,42] VR-enhanced science courses are also being developed in schools to help students better understand complex topics through interactive models and virtual laboratories.

In Thailand, VR technologies are actively integrated into education, with universities developing virtual learning environments in fields like architecture, medicine, and natural sciences, and VR being used in schools to immerse students in historical events and natural phenomena. This enhances learning effectiveness and student engagement. For Bulgaria and Ukraine, strengthening collaboration between educational institutions and VR technology companies is recommended. Partnerships with local providers, such as VR City and VR Express, can help create VR-adapted curricula, particularly in disciplines like medicine and engineering. Additionally, teacher training and research on VR's impact on learning outcomes will support effective integration of VR, ultimately improving the quality of education.

Saeedian et al.[43], in a systematic review, summarise experimental and quasi-experimental data: interventions that specifically address the needs for autonomy, competence, and relatedness consistently increase adherence to behavioural protocols and the quality of outcomes, with the decisive factor being not the "intensity" of motivation, but its quality (a shift towards autonomous forms of regulation). Dempsey et al.[44] demonstrate in school samples that in vulnerable groups (girls, students with SEN, low SES), it is the experience of choice, transparent criteria for success, and a sense of belonging that are associated with better well-being and learning attitudes; i.e., supporting basic needs acts as a mechanism for reducing inequalities. Huang et al.[45] demonstrate, in student samples, a clear mediation pathway in which social support and empowerment increase autonomous motivation, which in turn translates into actual behaviour; access to control and timely feedback shift regulation from controlled to autonomous and make efforts more sustainable. Teng[46] in a longitudinal design in the context of GenAI, finds that identified/intrinsic motivation is a better predictor of sustained engagement and progress than external or introjected forms, and therefore, qualitative changes in motivation have a cumulative effect over time. Taken together, these results converge into two practical guidelines for VR in teacher training: learning scenarios should create real conditions for choice, gradual growth in competence, and social interaction (to nurture autonomous motivation), and the design of the environment should provide transparent feedback and a tangible locus of control so that the transfer of positive effects is maintained beyond the individual session. Comparable conclusions were drawn by Lydia et al.[47], who studied the impact of online tools on students' learning experiences and identified VR as one of the most promising areas within digital education.

The systematic reviews and meta-analyses referenced offer beneficial details about the effectiveness of immersive technologies, such as VR and AR, in educational contexts. García-Robles et al.[48] demonstrate that both VR and AR can significantly enhance anatomy education by providing immersive and interactive learning experiences, improving student engagement and knowledge retention. This aligns with the growing trend of incorporating VR and AR into medical and scientific education, offering students the opportunity to explore complex anatomical structures in a risk-free, virtual environment. Park et al.[49] emphasize the positive effects of immersive technology-based education on nursing students, showing improvements in both knowledge acquisition and student confidence. This study, using the GRADE approach, highlights the value of immersive technologies in professional education, particularly in healthcare, where practical training is crucial but often challenging to simulate with traditional methods.

Cromley et al.[50] contribute to the broader understanding of VR in STEM education, showing that VR can enhance learning outcomes across various STEM fields. Their findings suggest that virtual reality's interactive and immersive nature fosters deeper understanding, making it a valuable tool in disciplines like engineering and physics, where abstract concepts are often difficult to visualise. Li et al.[51] focus on the role of AR in higher education, providing a comprehensive review of its application from 2000 to 2023. Their findings underscore the potential for AR to enrich learning by offering context-specific visualisations, especially in fields that require hands-on learning. This study highlights AR's ability to bridge the gap between theoretical knowledge and practical experience, complementing VR's capabilities in immersive learning environments.

Bulgaria could benefit from studying the Netherlands' experience with VR in education. Dutch institutions integrate VR to explore complex scientific concepts, enhancing understanding and student engagement. The Netherlands has developed national programs to integrate ICT competencies, which support the adoption of emerging technologies. Adapting these practices in Bulgaria could improve educational quality and increase student engagement.

Comparing the use of virtual reality technologies in Bulgaria, Ukraine, and Thailand is essential for understanding the different approaches to integrating VR into the educational process and for identifying the factors that influence the success of its implementation. Bulgaria, as a member of the European Union, has access to advanced technologies and educational programs; however, VR integration remains limited, particularly in the school sector. Ukraine, which is actively advancing digital education, is implementing VR through targeted initiatives in higher education and medical institutions but generally faces challenges in terms of scalability and access to equipment. In contrast, Thailand makes significant progress due to strong government support, well-developed infrastructure, and comprehensive teacher training programmes. These factors have enabled the effective integration of VR into both school and university education.

The study makes a distinct contribution to the field by advancing the understanding of how VR-based pedagogical innovations can be systematically implemented and evaluated within teacher education. While previous research has established the general effectiveness of VR for learning, this study is unique in its use of a randomized controlled design, its focus on future educators as the target population, and its attention to inclusion through socioeconomic and disability subgroup analyses. The introduction of a replicable implementation algorithm and clearly defined contamination safeguards contributes to methodological transparency and practical applicability. Moreover, by situating the research within the Bulgarian higher education context, where empirical evidence on immersive pedagogy is scarce, the study provides valuable region-specific insights that expand global discussions on equitable and sustainable digital education.

Throughout the intervention, minor adverse effects were recorded among 7.3% of participants (n = 22), primarily including transient dizziness, mild headaches, and brief visual discomfort, which resolved spontaneously within minutes. No severe or prolonged cybersickness episodes were reported. Preventive measures included limiting VR exposure to 20-minute sessions, providing short breaks, and calibrating headsets for interpupillary distance before each use. Hygiene and safety protocols were rigorously followed: all VR headsets were disinfected with alcohol-free wipes after each session, and disposable hypoallergenic face covers were used to ensure skin protection and reduce microbial contamination risk.

In terms of scalability, the cost-per-student estimate for the pilot implementation averaged €95, including equipment amortisation and maintenance. The core investment comprised six mid-range VR headsets (approx. €450 each), one compatible workstation (€1,200), and software licenses (€300 per semester). To enhance scalability, a shared-equipment model was adopted, allowing small-group rotation (5–6 students per headset) without compromising engagement. This approach reduced overall expenses by approximately 60% compared with individual-device deployment. The study demonstrates that, with proper hygiene management and shared-access strategies, VR integration can be both safe and economically viable for medium-scale educational implementation.

## Conclusions

This study introduces a distinctly pragmatic implementation model validated through a large-scale randomized controlled trial within the Bulgarian higher education system, a context where empirical evidence remains limited. The study's innovation lies not only in its methodological rigor but also in its operational algorithm for integrating VR into teacher training, emphasizing contamination safeguards, subgroup inclusivity, and real-world feasibility. By focusing on future educators rather than general students, the research expands understanding of how immersive technologies can shape pedagogical competence, classroom management skills, and inclusivity practices. The findings have practical implications for policymakers and higher education administrators seeking scalable, cost-effective frameworks for technology adoption, marking a significant regional contribution to evidence-based digital pedagogy and sustainable educational reform.

VR in education allows the creation of virtual laboratories and simulations, enabling students to develop practical skills in a safe environment, especially in disciplines where real-life mistakes can be costly. It provides real-time feedback, boosting confidence and improving knowledge retention. However, challenges such as the high cost of hardware and the need for new teaching methodologies remain. To successfully integrate VR, it is necessary to invest in infrastructure, offer continuous training for educators and students, and modify curricula to accommodate VR, ultimately improving educational quality and outcomes. The study found that the experimental group, which utilised VR for teaching, achieved higher results compared to the control group, which employed traditional methods. This finding highlights the effectiveness of integrating VR into the educational process, as the technology facilitates deeper assimilation of learning material and enhances student motivation.

Using VR technologies in schools can make a big difference in quality, especially in Bulgaria, Ukraine, and Thailand. Key measures include VR-based courses, teacher training programmes, and increased investment in educational infrastructure. In Ukraine, digitising education, expanding access to VR equipment, and adapting curricula are priorities. Strategic cooperation with international technology companies and the modernisation of educational institutions in Thailand support interactive learning. The impact of VR tools on students' creative thinking and innovative capacities requires further research.

This study combines a large-scale randomised experiment on teacher training in Bulgaria with a VR implementation algorithm suitable for scaling. The research addresses inclusion issues by testing effects by socioeconomic status and disability, promoting equal access. The proposed algorithm combines sequential steps for integrating VR into teacher training curriculum, infrastructure, staff training, safety protocols, anonymising materials, and assessment rubrics. This work adds an empirically grounded "operating manual" for teacher training systems in Central and Eastern European countries, addressing budget constraints, unequal access, and evidence-based solutions.

The study acknowledges several limitations, particularly related to the high cost of VR equipment and software, which may restrict its widespread adoption in educational institutions with limited budgets. Technical barriers, such as the need for specialised infrastructure and teacher training, further challenge the effective implementation of VR. The generalisability of the findings is also a concern, as the study was conducted at a single university, and the sample may not fully represent the broader population of educators and students across different regions or educational levels. These factors must be considered when scaling VR technologies for broader use in education.

## Implications

The integration of VR technologies in education can significantly enhance student engagement and learning outcomes. It is recommended that institutions invest in VR-adapted curricula and collaborate with VR technology providers to create specialized courses. Teacher training and support are essential for effective VR implementation. Addressing challenges like high equipment costs and technical barriers is crucial for widespread adoption. Further research is needed to assess VR's long-term impact and identify best practices for its integration.

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