ПРИКЛАДНЫЕ ИССЛЕДОВАНИЯ

Problems and solutions in using 3D modeling and virtual reality technologies for creating immersive learning

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Abstract

This article is devoted to a comprehensive assessment of the effectiveness and challenges arising from the integration of 3D modeling and virtual reality (VR) technologies into the educational process to create an immersive learning environment. The aim of the study was to identify both the positive effects and the key barriers hindering the widespread adoption of these technologies. To achieve this goal, a quasi-experimental study was conducted at a technical university with the participation of 120 students. The participants were divided into an experimental group, which studied the design of a planetary gearbox using a specialized VR module, and a control group, which was taught using traditional methods with drawings and physical models. Learning effectiveness, engagement, cognitive load, and cybersickness symptoms were assessed through a combination of quantitative (testing, UES questionnaires, NASA-TLX, SSQ) and qualitative (interviews, focus groups) methods. The analysis of the results demonstrated a significant advantage of the immersive approach. The increase in academic performance in the experimental group amounted to 27,1%, which was more than twice the level of the control group (9,45%). Students working in VR demonstrated significantly higher levels of engagement, a sense of immersion, and gave positive feedback on the clarity of the material, which contributed to a deeper understanding of complex spatial structures. At the same time, the study also objectively revealed serious problems. A high cognitive load on students in the VR environment was recorded (average NASA-TLX score – 68.45 out of 100), as well as the presence of cybersickness symptoms in a significant proportion of users (average SSQ score – 18.21), manifested in disorientation and visual strain. Qualitative analysis confirmed that along with high motivation and the safety of virtual experiments, students encountered technical malfunctions, difficulties adapting to controls, and a feeling of social isolation. Thus, the study concludes that despite the proven high educational effectiveness, the successful implementation of VR technologies requires a systematic approach. It is necessary not only to create high-quality content but also to develop methods aimed at reducing cognitive load and minimizing physiological discomfort, for example, by limiting session duration and introducing hybrid learning formats that combine individual work in VR with group discussions.

Keywords
immersive learning, virtual reality, 3D modeling, cybersickness, cognitive load.

Introduction

The modern educational paradigm is undergoing significant transformations due to the rapid development of digital technologies. In this context, 3D modeling and virtual reality (VR) technologies are among the most promising tools for creating immersive learning. Immersive learning allows students to actively interact with three-dimensional objects and environments rather than just passively perceive information, which contributes to a deeper understanding of complex concepts and the development of practical skills in a safe, controlled environment. The use of VR in education opens up opportunities for modeling situations that are impossible or too expensive to recreate in reality, whether it is a surgical operation, the management of complex industrial equipment, or the study of historical monuments in their original form (Parchuk, 2023). The potential of these technologies lies in their ability to visualize abstract data, turning it into tangible and interactive models. This is especially true for disciplines such as medicine, engineering, architecture, and natural sciences, where spatial imagination and understanding the relationships between system elements play a key role (Davydova, 2023).

Despite the obvious advantages, the widespread introduction of 3D modeling and VR in the educational process faces a number of serious problems. One of the main obstacles is the high cost of the necessary hardware and software. Powerful computers capable of processing complex 3D graphics in real time, and high-quality VR headsets are still financially inaccessible for many educational institutions. In addition, creating high-quality educational content requires the involvement of highly specialized professionals: 3D artists, programmers, game design specialists, and, importantly, methodologists who can competently integrate technology into the curriculum. There is also a pedagogical problem: many teachers do not have sufficient competencies to work with new tools and have difficulties adapting traditional teaching methods to an immersive environment (Chen, 2024). Finally, the physiological aspects of VR use cannot be ignored, in particular, the problem of cyberbullying (simulation malaise), which can cause users nausea, dizziness and disorientation, which significantly reduces the effectiveness of training and limits the duration of training sessions. Solving these complex problems requires a systematic approach that includes both technological innovations and the development of new pedagogical strategies.

Materials and research methods

To study the effectiveness and identify problems of using immersive technologies in teaching, a quasi-experimental study was conducted at the technical university. The study involved 120 third-year students studying the discipline «Machine parts and design basics». Participants were randomly divided into two equal groups: experimental (n=60) and control (n=60). For the experimental group, a specialized training module was developed in a virtual reality environment dedicated to the assembly and analysis of the planetary gearbox operation. The content was created using Autodesk Inventor 3D modeling software and the Unity game engine, and Oculus Quest 2 standalone VR headsets were used as equipment. Students of the experimental group were trained for one academic semester, combining traditional lectures with practical VR classes, each lasting no more than 45 minutes to minimize risk cyber diseases (Kiryukhina, 2023). The control group was trained on the same topic, but using standard methods: lectures, practical exercises using two-dimensional drawings and physical layouts (Shishov, 2022).

Data collection was carried out using a comprehensive approach, including quantitative and qualitative methods. To assess the academic performance of both groups, preliminary and final testing was used, consisting of theoretical questions and practical tasks to understand the principles of operation and design of the gearbox. The level of student engagement in the learning process was measured using a validated User Engagement Scale (UES) questionnaire, which evaluates aspects such as focused attention, perceived usability, aesthetic appeal, and a sense of immersion. To assess the cognitive load on students of the experimental group after each VR session, the NASA-TLX (Task Load Index) method was used. At the same time, the SSQ (Simulator Sickness Questionnaire) questionnaire was used to identify symptoms of cyberbullying (Bolbakov, 2022). Qualitative data were collected through semi-structured interviews with students of the experimental group and focus groups aimed at identifying their subjective perception of the advantages and disadvantages of VR training (Platonova, 2025). Statistical processing of quantitative data was carried out using the Student's t-test for independent samples to compare the average values between groups, as well as correlation analysis to identify relationships between various indicators within the experimental group (Chumak, 2024).

Results and discussion

The conducted research was aimed at quantitative and qualitative assessment of the impact of immersive technologies on the educational process, as well as at identifying key problems that accompany their implementation. The main focus was on comparing the academic performance, level of engagement and cognitive load of students who studied using traditional methods and using virtual reality. The analysis of the obtained data allowed us not only to confirm a number of hypotheses about the benefits of VR, but also to objectify existing barriers, which is critical for developing effective strategies for integrating these technologies into education.

The first stage of the analysis was to compare the results of final testing in the control and experimental groups to assess the direct impact of the VR module on material assimilation. The results of preliminary testing showed no statistically significant differences in the level of training of students in both groups, which confirms the correctness of their initial separation. However, the final data show significant discrepancies in the growth of knowledge, which is described in detail in the comparative analysis of academic performance (Table 1).

Table 1. Comparative analysis of academic performance

Group	Average score before the experiment (out of 100)	Average score after the experiment (out of 100)	Academic achievement gain, %	Standard deviation of growth, %
Control (n=60)	65.18	71.34	9,45	3,12
Experimental (n=60)	64.95	82.55	27,10	5,88

The analysis of the data presented in Table 1 demonstrates a significant superiority of the experimental group in all key indicators of learning effectiveness. The average score of students who used VR technologies after the experiment reached 82.55, while in the control group this indicator was only 71.34. The most significant difference is the percentage increase in academic performance: 27,10% in the experimental group versus 9,45% in the control group. This indicates that immersive interaction with a three-dimensional model of the gearbox allowed students to better understand its design and operating principles compared to studying two-dimensional drawings and static layouts.

A higher standard deviation of the gain in the experimental group (5,88% vs. 3,12%) indicates greater variability in the results. This may be due to individual differences in the perception of the VR environment and the level of digital literacy of students. Some students were able to maximize the benefits of the technology, which led to outstanding progress, while others may have found it difficult to adapt to the new learning format (Isakieva, 2024). Nevertheless, even taking into account this variability, the minimum increase in the experimental group was higher than the average increase in the control group, which indisputably proves the overall effectiveness of the applied approach.

The next step was to assess the students ' subjective experience, in particular, their involvement in the learning process. This parameter is key, since high engagement directly correlates with motivation and the quality of learning the material. For this purpose, the UES scale was used, the results of which for both groups are summarized in a table (Table 2).

Table 2. Assessment of student engagement on the UES scale (average score on a 5-point scale)

Engagement component	Control group (average score)	Experimental group (average score)	Statistical significance (p-value)
Focused Attention	3.45	4.62	<0.001
Perceived Usability	4.12	3.88	>0.05
Aesthetic Appeal	2.89	4.75	<0.001

Sense of Immersion	2.54	4.81	<0.001

The data in Table 2 clearly indicate a significantly higher level of involvement in the experimental group. For such components as «Focused attention», «Aesthetic appeal» and «Sense of immersion», the difference is statistically significant ($p<0.001$). The average score for «Immersive Experience» in the VR group (4.81) is almost twice that of the control group (2.54), which is logically explained by the very nature of the technology. Students noted that the ability to «get inside» the mechanism and manipulate its details in three-dimensional space creates a unique and memorable experience. A high rating of aesthetic attractiveness (4.75) also played an important role in increasing motivation (Chernoyarova, 2023).

It is interesting to note that in the «Perceived usability» component, the control group showed a slightly better result (4.12 vs. 3.88), although the difference is not statistically significant. This indicates one of the key problems of VR technologies: the interface and management in a virtual environment may still be less intuitive for an untrained user compared to the usual methods of working with drawings and layouts. Some students in interviews noted the need for time to adapt to controllers and navigation in virtual space, which at the initial stage created certain difficulties.

Despite the obvious success in academic performance and engagement, it was also important to assess the negative aspects of VR use, namely cognitive load and the risk of cyber-pain. These factors can be a serious obstacle to mass adoption of the technology. The results of evaluating these parameters in the experimental group are presented below (Table 3).

Table 3. Analysis of cognitive load and symptoms of cyberbullying in the experimental group

Indicator	Average value	Standard deviation	Range of values (Min-Max)
Cognitive load (NASA-TLX, scale 0-100)	68.45	12.33	45-92 Cyber-pain
Index (SSQ, total score)	18.21	9.57	0-45.6

The results presented in table 3 highlight the other side of the coin. The average level of cognitive load measured on the NASA-TLX scale was 68.45, which is quite high and indicates significant mental effort required from students during VR sessions. A large standard deviation (12.33) and a wide range of values (from 45 to 92) indicate that students perceived the complexity of the problem very differently. This may be due to both individual cognitive abilities and previous experience of interacting with 3D environments.

An even more serious problem is the presence of symptoms of cyber-illness. The average overall score on the SSQ questionnaire was 18.21, which corresponds to a mild or moderate level of discomfort. Although some of the students had no symptoms at all (minimum value 0), some of them reached high levels (maximum 45.6), which required immediate termination of the session. The most common complaints were general disorientation, eye strain, and mild nausea (Kurzaeva, 2023). These data confirm that physiological discomfort is a real and significant barrier that requires careful consideration both at the level of technical content optimization (stable frame rate, minimizing delays) and at the level of methodology (limiting session time, introducing breaks).

To get a complete picture, we analyzed qualitative data obtained during interviews and focus groups. The main topics identified by students as advantages and disadvantages of VR training were systematized and presented in the form of frequency analysis (Table 4).

Table 4. Qualitative assessment: main identified problems and benefits (based on interviews)

Category	Topic	Frequency of mentions, %
Advantages	Visibility and better understanding of the space	91,5
	High engagement and interest	84,7
	Security (possibility of making mistakes)	72,9
	Gamification and interactivity	66,1
Problems	Technical glitches and configuration difficulties	55,9
	Physical discomfort (cyber pain, eye fatigue)	42,4

	Need to adapt to management	37,3
	Isolation from the group and the teacher	20,3

Qualitative analysis fully confirms and complements quantitative data. The vast majority of students (91.5%) noted unprecedented visibility as the main advantage of VR, which directly explains the increase in academic performance (Table 1). High engagement (84,7%) correlates with the data from Table 2. Such an important aspect as safety, that is, the ability to repeatedly disassemble and assemble a complex mechanism without the risk of damage, was noted by 72,9% of respondents (Bolbakov, 2023). This is a key advantage for learning practical skills.

Among the problems, in addition to the already identified cyber-pain (42,4%), students often pointed out technical failures (55.9%), such as program freezing or loss of controller tracking, which disrupted the immersion process and caused frustration (Tatarinov, 2024). The problem of isolation from the group was also noted (20,3%), since during a VR session the student is «one on one» with the virtual world, which makes it difficult to communicate with the teacher and other students. This highlights the need to develop multi-user VR environments or hybrid learning formats, where individual work in VR is combined with group discussion (Shevlyakova-Borzenko, 2023).

A comprehensive analysis of all four tables allows us to form a multi-faceted view of the use of VR in technical education. A comparison of the data from Tables 1 and 2 shows that a significant increase in academic performance in the experimental group is not an accident, but is directly due to a qualitatively different level of student engagement. Aesthetic appeal and a sense of immersion, which reach almost maximum values in the VR environment, transform passive knowledge acquisition into an active research process, which leads to a deeper and stronger assimilation of the material. Thus, investing in creating visually rich and interactive content directly pays off with educational results.

On the other hand, the comparison of academic performance data (see Table 1). 1) with data on cognitive load and cyberbullying (tab. 3) reveals a fundamental trade-off. The effectiveness of training is achieved at the cost of high cognitive load and the risk of physical discomfort. A high average score on the NASA-TLX scale suggests that VR training is intense mental work, and not just entertainment. This fact should be taken into account when planning the training load and duration of classes. The presence of symptoms of cyberbullying in a significant part of students (tab. 3) and frequent references to it in interviews (Table 1). 4) are the most serious obstacle that needs to be addressed immediately.

Integration of qualitative and quantitative data (Table 4 in conjunction with Tables 1-3) makes it possible to develop specific recommendations. For example, the identified problem «Technical failures» (55,9%) and the average score on «Perceived usability» (3.88) indicate the need not only to improve the software itself, but also to conduct a preliminary briefing and adaptation period for students. The problem of «Isolation» noted in the qualitative analysis calls into question the effectiveness of fully individualized VR training and pushes for the development of joint virtual laboratories where students and teachers can interact in a common virtual space.

Thus, mathematical and qualitative data processing shows that the way to effective immersive learning is through balance. You need to maximize the benefits of VR, such as visibility and engagement, by purposefully working to minimize its disadvantages. Solutions should be complex: technological (performance optimization, development of intuitive interfaces), methodological (development of pedagogical scenarios, load batching, hybrid learning formats) and organizational (teacher training, technical support). Only such a systematic approach will allow us to fully unlock the huge potential of 3D modeling and virtual reality for the education of the future (Maltseva, 2024).

Conclusion

The study convincingly demonstrated that the integration of 3D modeling and virtual reality technologies can dramatically improve the effectiveness of the educational process, especially in technical disciplines. It was found that students who studied using the immersive VR module showed a statistically significant increase in academic performance, which was more than twice as high as the control group that studied using traditional methods. This success is directly related to qualitative changes in the learning experience: the technology provides an unprecedented level of visibility, allows you to safely interact with complex objects and creates a strong immersion effect, which together leads to a significant increase in student engagement and motivation. The ability to manipulate three-dimensional models, explore their internal structure and observe dynamic processes in real time contributes to the formation of a deep, intuitive understanding of the material, which is difficult to achieve using two-dimensional drawings or static layouts.

At the same time, the study identified and systematized a set of problems that hinder the widespread and unhindered introduction of VR in education. The key barriers are a high cognitive load on students and a significant risk of cyber-pain, which requires a careful approach to content design and organization of the educational process, including limiting the duration of sessions and individual adaptation. Technical aspects, such as software failures and the need to get used to control systems, also reduce overall efficiency and can cause frustration for users. Finally, the problem of potential social isolation when working individually in VR was highlighted. To overcome these challenges, a systematic approach is needed, including not only technological improvement of equipment and software, but also the development of new pedagogical models focused on hybrid learning. The success of immersive education depends on the ability to find a balance between using the powerful capabilities of VR and creating a comfortable, safe and methodically sound learning environment.

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Проблемы и решения при использовании 3D-моделирования и технологий виртуальной реальности для создания иммерсивного обучения

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Аннотация

Настоящая статья посвящена комплексной оценке эффективности и проблем, возникающих при интеграции 3D-моделирования и технологий виртуальной реальности (VR) в образовательный процесс для создания иммерсивной учебной среды. Целью исследования было выявить как положительные эффекты, так и ключевые барьеры, препятствующие широкому внедрению данных технологий. Для достижения этой цели было проведено квазиэкспериментальное исследование на базе технического университета с участием 120 студентов. Участники были разделены на экспериментальную группу, которая изучала конструкцию планетарного редуктора с помощью специализированного VR-модуля, и контрольную группу, обучавшуюся по традиционным методикам с использованием чертежей и физических макетов. Эффективность обучения, вовлеченность, когнитивная нагрузка и симптомы киберболезни оценивались с помощью комплекса количественных (тестирование, опросники UES, NASA-TLX, SSQ) и качественных (интервью, фокус-группы) методов. Анализ результатов продемонстрировал значительное преимущество иммерсивного подхода. Прирост академической успеваемости в экспериментальной группе составил 27,1%, что более чем в два раза превысило показатель контрольной группы (9,45%). Студенты, работавшие в VR, показали значительно более высокий уровень вовлеченности, чувства погружения и положительно оценили наглядность материала, что способствовало более глубокому пониманию сложных пространственных конструкций. Вместе с тем, исследование объективизировало и серьезные проблемы. Была зафиксирована высокая когнитивная нагрузка на студентов в VR-среде (средний балл по шкале NASA-TLX – 68,45 из 100), а также наличие симптомов киберболезни у значительной части пользователей (средний балл по SSQ – 18,21), что выражалось в дезориентации и зрительном напряжении. Качественный анализ подтвердил, что наряду с высокой мотивацией и безопасностью виртуальных экспериментов, студенты сталкивались с техническими сбоями, сложностями в адаптации к управлению и ощущением социальной изоляции. Таким образом, исследование заключает, что, несмотря на доказанную высокую образовательную эффективность, успешное внедрение VR-технологий требует системного подхода. Необходимо не

только создавать качественный контент, но и разрабатывать методики, направленные на снижение когнитивной нагрузки и минимизацию физиологического дискомфорта, например, путем ограничения длительности сессий и внедрения гибридных форматов обучения, сочетающих индивидуальную работу в VR с коллективным обсуждением.

Ключевые слова
иммерсивное обучение, виртуальная реальность, 3D-моделирование, киберболезнь, когнитивная нагрузка.

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