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The potential of virtual reality in modelling complex scientific processes for distance education: a scoping review

El potencial de la realidad virtual en el modelado de procesos científicos complejos para la educación a distancia: una revisión del alcance

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Abstract

The contemporary impact of digital technologies is evident in educational transformations, particularly in remote learning. This article aims to investigate the potential of virtual reality in modelling complex scientific processes within the distance education framework. To achieve this objective, scientific methods of comparison and synthesis were employed. The study is based on the PRISMA approach, with 74 literature sources reviewed. The findings indicate that VR is particularly relevant for higher education (in various fields such as technical, social sciences, and medicine) through the application of synchronous collaboration between different technologies (virtual and augmented realities). Special emphasis is placed on the importance of motivation as a key component of distance learning, mainly when using VR technologies. It is suggested that the use of VR technologies holds promise, offering interactive learning environments, creating individual educational trajectories, and reducing financial costs. However, challenges include a lack of realism, socio-pedagogical issues, and the high equipment cost. The conclusions highlight that overcoming these challenges will require implementing comprehensive programmes for funding and mastering new technologies.

Keywords: interactive learning, simulation of scientific experiments, educational technologies, data visualisation.

Resumen

El impacto contemporáneo de las tecnologías digitales es evidente en las transformaciones educativas, particularmente en el aprendizaje a distancia. Este artículo tiene como objetivo investigar el potencial de la realidad virtual en el modelado de procesos científicos complejos en el marco de la educación a distancia. Para lograr este objetivo, se emplearon métodos científicos de comparación y síntesis. El estudio se basa en el enfoque PRISMA, con 74 fuentes bibliográficas revisadas. Los hallazgos indican que la realidad virtual es particularmente relevante para la educación superior (en varios campos como las ciencias técnicas, sociales y médicas) a través de la aplicación de la colaboración sincrónica entre diferentes tecnologías (realidades virtuales y aumentadas). Se hace especial hincapié en la importancia de la motivación como un componente clave del aprendizaje a distancia, principalmente cuando se utilizan tecnologías de realidad virtual. Se sugiere que el uso de tecnologías de realidad virtual es prometedor, ya que ofrece entornos de aprendizaje interactivos, crea trayectorias educativas individuales y reduce los costos financieros. Sin embargo, los desafíos incluyen la falta de realismo, problemas sociopedagógicos y el alto costo del equipo. Las conclusiones destacan que superar estos desafíos requerirá implementar programas integrales para financiar y dominar nuevas tecnologías.

Palabras clave: aprendizaje interactivo, simulación de experimentos científicos, tecnologías educativas, visualización de datos.

Introduction

Over recent decades, digital technologies have demonstrated their influence across all spheres of social life, including the field of pedagogy. Modern gadgets offer opportunities to diversify traditional learning, enriching it with new approaches and methodologies. Given the rapid development of information technologies, it is clear that education will continue to evolve towards further digitalisation. This includes transformations in distance learning, which has already gained significant popularity due to various circumstances (e.g., the COVID-19 pandemic) thanks to its features, such as broad accessibility, interactivity, and the ability to incorporate tasks of varying difficulty levels. However, one of the main challenges for the further integration of distance education into the learning process is ensuring an adequate level of practical training for students, as required by the demands of the modern labour market (Leleka et al., 2024).

This issue has attracted the attention of researchers. Summarising brief excerpts from several studies, it can be stated that virtual reality provides opportunities to create interactive environments with a wide range of possibilities for multifaceted learning (Abichandani et al., 2019; Abumalloh et al., 2021; Zhang et al., 2020b). As a result, students can fully immerse themselves in the simulation process, interact with objects in real-time, and perform certain laboratory tasks in a safe environment under the supervision of academic mentors. The availability of such interactive and visually rich tools opens up opportunities for enhancement (Yan et al., 2020; Wang et al., 2019). The use of digital technologies is driven by the fact that conducting experiments and accessing research equipment is challenging in the context of distance education (Chashechnikova et al., 2024; Potkonjak et al., 2016; Sarkar et al., 2021; Yemelyanova et al., 2022). VR technologies also enable a deeper understanding of complex scientific theories, as visualisation and the ability to actively participate in the scientific discovery process promote active learning, even in a distance format.

At the same time, researchers have emphasised the relevance of using VR in the educational process, identifying both the advantages and disadvantages of this tool (Paramita et al., 2021; Nisiotis & Kleanthous, 2019). Notably, there are strong arguments from scholars who believe that VR digital technologies offer students the potential to improve the quality of the educational process, including access to virtual laboratories or other resources that enable interactive engagement (Mozelius et al., 2020). Some even suggest that VR technologies are among the most promising, as they significantly reduce the cost of experimental processes during learning, simplifying (and automating) the work of teachers preparing tasks and lab assistants responsible for the material aspect of experiment provision (Kumar, 2024; Irwansyah et al., 2020; Herwig et al., 2018).

However, it is important to consider the opinions of researchers who analyse the students' perspectives: these studies have highlighted that virtual reality, at its current stage of technological development, differs from real-world experimental conditions, which may lead to misunderstandings of fundamental processes occurring in practice (Grunewald Nichele & do Nascimento, 2017; Gargano et al., 2018). From this perspective, it seems reasonable to agree with scholars who acknowledge the potential of VR development but note that such potential will only be realised with further improvement of education (de Moraes Rossetto et al., 2023; Cobo & Rivas, 2023; Dubiaha et al., 2022). Considering this evolution may influence key directions in the application of virtual reality technologies (Gargano et al., 2018). The integration of VR into the simulation of scientific processes and the assessment of its effectiveness remain pertinent issues.

The aim of this article is to explore the potential of virtual reality in modelling complex scientific processes within the context of distance education. Achieving this aim will require the completion of specific tasks to facilitate its realisation. These tasks include analysing relevant scientific literature, identifying the main vectors for applying VR in education, evaluating the tools, results, and outcomes of using these technologies, and examining relevant scholarly views on the prospects and challenges of employing VR technologies in distance education.

Materials and Methods

Design of the study

This study is based on a scoping review and is classified as a quantitative work. The research incorporates various materials, including academic articles, monographs, and conference proceedings. The date range spans from 2018 to 2024. This timeframe was chosen to ensure the inclusion of only current and relevant information present in contemporary academic studies.

Sample

The sample included various sources, including articles, monographs, and conference proceedings. The primary focus was on whether these works were peer-reviewed and included in reputable scientometric databases. No strict or specific geographical focus was applied; the study included research from authors across different parts of the world.

Instruments and procedure

This scoping review was conducted using a phased and systematic approach based on the PRISMA framework. The selected scientometric databases were Google Scholar and Web of Science. Key terms such as "distance education," "technologies," "virtual reality," "digital technologies," and "skills" were used in the search queries on these platforms. A total of 17,400 results were found. Initially, all duplicates were removed—8,000 in total. Articles that were unrelated to modern education and those authored by Russian scholars were excluded (-3,000). The next stage involved screening, leaving 6,400 works for further consideration. Subsequently, an analysis of the abstracts was carried out, and works unrelated to the chosen topic were discarded (-2,354). The inclusion criteria focused on the following aspects:

1. The study pertains to the implementation of virtual reality.
2. The study relates to distance education.
3. The study describes the outcomes of virtual reality implementation.
4. Language of publication: English.
5. Date range: 2018-2024, with some studies beyond this period included due to their relevance to this research.

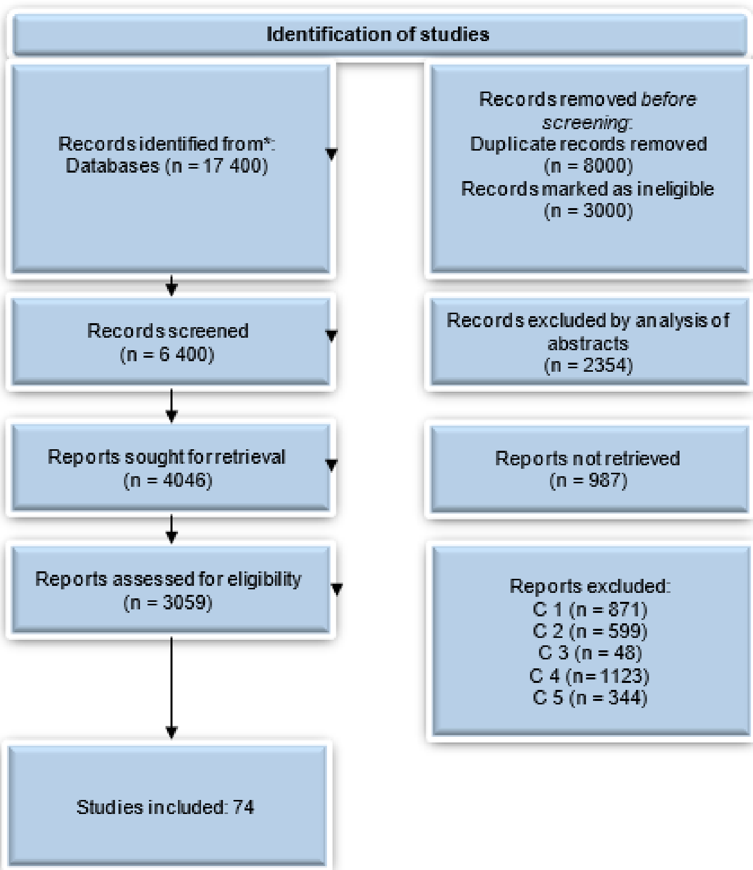

Figure 1. PRISMA-compliant data collection, identification and screening.
Source: compiled by authors.

Thus, 81 literature items were selected and subjected to analysis based on a strict selection of scientific sources.

Data analysis

Excel software was selected for data analysis. As the first indicator, elements related to forms of education were measured. Key data from the selected studies, such as the author, year of publication, mode of education, virtual reality application, type of learning, objective, and software, were entered into the first Excel table. This allowed for identifying the main directions and purposes of using this technology. The second dimension of this scoping review focused on a more detailed examination of the systems used in the selected studies. Accordingly, another table included data such as the author, year of publication, software, and system. This enabled a characterisation of the primary virtual systems utilised in modern educational institutions. A separate table was dedicated to overall measurement indicators, methods, and research tools. Through comparative analysis, it was possible to compare the obtained data with the findings of other authors.

Results

As the first indicator, elements related to forms of education were measured. Most of the selected research studies focused on implementing VR in higher education. Although the topics of these studies were broad, the most discussed fields were technical sciences, social sciences, and medicine. Many studies also concentrated on the synchronous collaboration of different technologies, particularly virtual and augmented reality. Synchronous (collaborative) interaction was covered in 64% of the analysed studies, compared to a significantly lower 19.7% for asynchronous collaboration.

Secondary education was the primary focus of 10.8% of the articles, while the implementation of VR in primary education was highlighted in 5.0% of the studies. This is generally a low figure compared to the high percentage (62%) of articles focusing on higher education. Only 4.5% of researchers examined the features of implementing virtual reality outside formal education, such as training in workplace environments. Regarding key aspects of teaching practice, almost half of the selected articles reported that educators supported learners (55.4%). In 20.9% of cases, teachers delivered lectures and presentations as part of professional training, providing a more passive learning environment. In terms of the purpose of using virtual reality, it was primarily employed to develop practical skills, enhance cognitive abilities, support collaboration, and increase student motivation (Table 1).

Table 1.
Forms, directions, types of learning and purposes of using VR

Class and feature (N = 81)	Value (%)
Form of education	
Higher education	62%
Secondary education	10.8%
Primary education	3%
Trainings (outside formal education)	4.5%
Other form - not specified - not proven	19.7%
Directions for using VR	
Social sciences	11.5%
Technical sciences, computer sciences, robotics, engineering	12.2%
Medicine	9.5%
Mathematics and physical sciences	6%
Life sciences	4.5%
Business and management	4.5%
Education, pedagogy	26.8%
Not specified	25%
Type of education	
Synchronous	64%
Asynchronous	19.7%
Not specified, another form	16.3%
Purpose of education	
Development of practical skills	25%
Collaboration, formation of motivation	14%
Cognitive abilities	19.7%
Greater student involvement	19.7%
Not specified	21.6%

Source: compiled by authors

On a larger scale, studies have shown that virtual reality is used in various scientific fields and specialities: education and pedagogy (26.8%), computer science, robotics, ICT and informatics (12.2%), social sciences (11.5%) and medicine (9.4%) (See Figure 2).

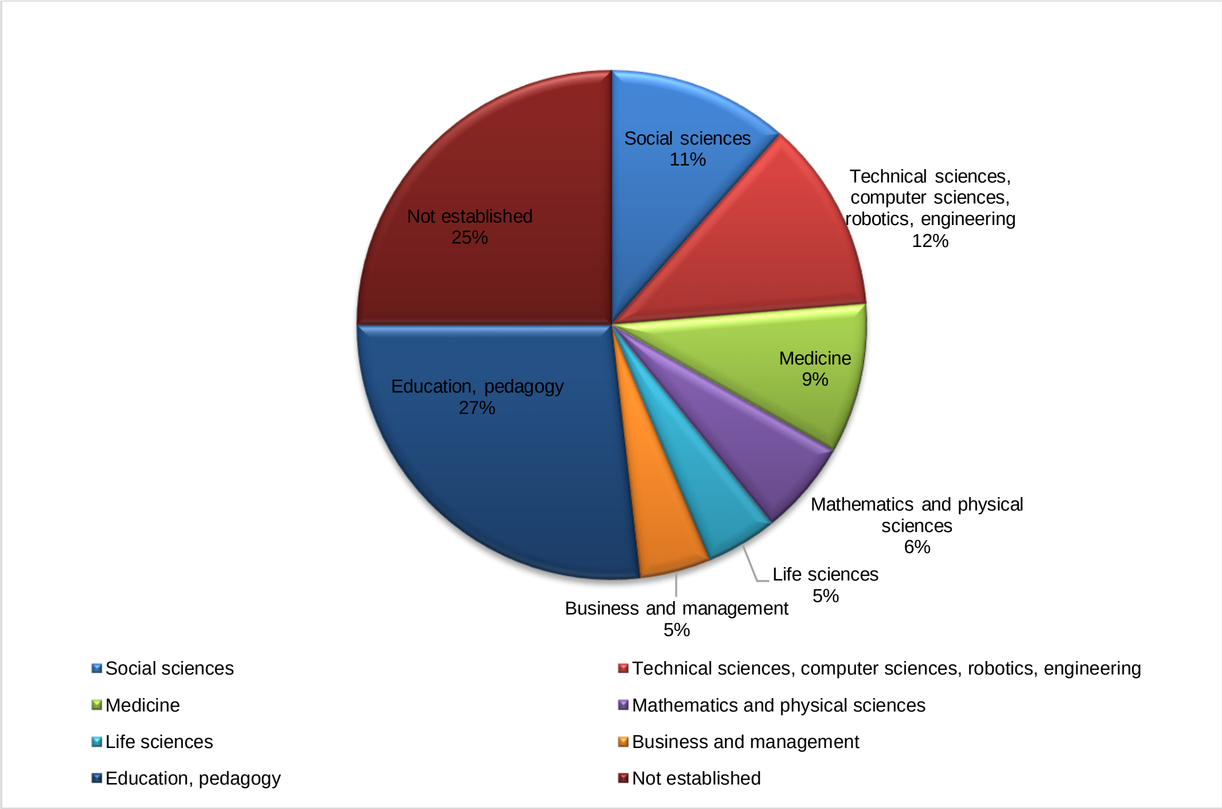

***Figure 2**.* Main educational fields of VR use.
Source: compiled by authors

The use of virtual reality to develop practical skills is a popular direction. Also, taking into account learning objectives, the development of cognitive abilities and greater student engagement are popular areas of research.

The second dimension of this scoping review is devoted to a more detailed study of the systems used in the selected studies. In particular, attention is paid to elements related to hardware (devices, control types) and how users interact with VE (virtual embodiment, degree of virtuality). In the VRCL study, most of the research reviewed focused on monitors and displays rather than VR technologies such as HMD-based VR (HMD VR).

In contrast to the common AR/MR (35%) and HMD VR (45%), the degree of virtuality in the reviewed studies was significantly higher (80%), indicating a clear advantage of virtual simulation. To demonstrate VRCL environments, a significant proportion of the hardware used in these studies (89.2%) used flat panel monitors and screens. These studies often used desktop computer configurations with a keyboard (See Table 2).

Table 2.
Main systems, support and degree of virtuality

Class and feature (N = 81)	Value (%)
Degree of virtual	
Only HMD Virtual Reality	45%
Augmented/Mixed Reality	35%
3D Simulation (non-HMD)	20%
Hardware	
Monitor/display	35%
CAVE system	19.7%
HMDs and glasses	19.7%
Not specified	25.6%
System	
Prototype	35.6%
Application	64%
Not specified	1%

Source: compiled by authors

The virtual reality content used in digital or distance education systems varied significantly depending on the scope of each study, its objectives, and the type of learning involved. Some studies utilised theoretical knowledge acquisition methods and literature reviews (Soberanes-Martín, 2021; Bohomaz et al., 2023). However, the majority of the research employed experimental learning.

Type of research: 28% of the studies were theoretical or review-based. The remaining 72% consisted of empirical research articles. The selected empirical studies featured various target groups, with participant numbers ranging from 5 to 120. These studies predominantly involved students and educators and, in some cases, medical students and patients (in the context of medical education).

Assessment tools: Empirical studies employed various methods, including semi-structured interviews, self-assessment questionnaires, clinical tests, observation, supervision, and testing. Multiple-choice tests and other written materials were also used to assess knowledge in distance education systems. Educational initiatives were often evaluated using the Kirkpatrick model.

Focus: The selected studies primarily focused on improving student engagement and developing practical skills in virtual education. In medical education, the studies measured outcomes such as knowledge, key skills, confidence, learning effectiveness, and empathy. Table 3 presents the key metrics, including assessment tools, participants, and results.

Table 3.
Studies, metrics, tools, and outcomes of virtual reality use

Source	General indicators of measurement	Research tools	Results
Abdullah et al. (2019)	Knowledge, group work	Empirical indicators	Virtual reality greatly enhances teamwork skills
Adhikari et al. (2021)	Knowledge, practical skills, confidence	Questionnaire Semi-structured interview	Improves engagement and confidence
Andersen et al. (2021)	Knowledge, practical skills, efficiency	Testing	Improves formation of practical skills
Amini et al. (2021)	Empathy (KSA)	Testing Kirkpatrick's model	No significant difference was observed in the cognitive learning system.
Atta et al. (2022)	Practical skills, knowledge	Technical tools	Improve knowledge of space technologies
Chiang et al. (2022)	Practical skills, involvement	HMD-VR simulation, empirical indicators	Increasing self-efficacy and satisfaction with learning
Gunn et al. (2020)	Skill acquisition and confidence	Survey	Significantly improve confidence
Le & Nguyen (2020)	Acquisition of skills, formation of experience	Empirical indicators	Improve the process of acquiring skills
Mallik et al. (2021)	Confidence	Testing Kirkpatrick's model E-survey	The level of confidence has increased
Giordano et al. (2020)	Knowledge, experience, feeling	Survey	There is no noticeable difference compared to the post-test
Pérez et al. (2022)	Development of social skills	Qualitative, phenomenological study	Significant improvement in social skills
Hood et al. (2021)	Educational management process with the help of VR	Pilot study	Workflow optimisation in clinical settings
Osmanlliu et al. (2020)	Providing comfort	Pilot pragmatic randomised controlled trial	Improvement of comfort, acquisition of practical skills
Liu (2020)	Establishing empathy	vOSviewer Clustering and data visualisation	VR has provided a spectrum of latitude to establish empathy
Chaiyarak et al. (2021)	Knowledge, practical skills	Empirical indicators	Development of knowledge, skills, improvement of student engagement
Aebersold et al. (2018)	Interactivity, practical skills	Mixed study Survey Interview	Improvement of integrability
Bedregal-Alpaca et al. (2020)	Skills, theory	Theoretical study	Improving student engagement
Dhar et al. (2023)	Knowledge, skills, theory, confidence, experience	Scoping-review	Improving student engagement, experience and skills
Anthony Jnr & Noel. (2021)	Knowledge, skills	Assessment	Development of knowledge, skills, improvement of student engagement
Ergüzen et al. (2021)	Improvement of technological indicators	Experiment Survey	Improvement of technological infrastructure
Zhang et al. (2020a)	Quality, experience, and involvement of students	Survey	Improving students' abilities

Source: compiled by authors

Considering the results of virtual reality implementation, contemporary researchers note more positive aspects than negative ones. Based on the conducted analysis, existing challenges, as well as the prospects and difficulties of using VR technology in distance learning, have been identified (Table 4). It is important to highlight that this current understanding is formed from the examination of existing academic viewpoints, which does not preclude the possibility that new phenomena and technologies may emerge, leading to the revision, adjustment, or even rejection of the currently available perspectives.

Table 4.
Prospects and Challenges of Using Virtual Reality (VR)

Prospects	Difficulties
Creation of Interactive Environments. VR technologies provide opportunities for interactive engagement with complex scientific phenomena and processes in real time. This enables exploring processes that are difficult to replicate in standard conditions (Hubal, 2012; Rasulov, 2024).	Limitations of Realism in Conducting Classes. It is challenging to model certain physical phenomena that are directly influenced by external environmental conditions, such as temperature, gravitational force, and atmospheric pressure.
Personalisation. VR technologies are adaptable to creating personalised learning environments that cater to each student's needs. This versatility also allows for the effective integration of multiple disciplines.	Pedagogical and Social Challenges. The application of VR technologies necessitates updating pedagogical methodologies, as most contemporary knowledge is oriented towards traditional education models.
Reduction of Financial Costs and Increased Motivation. The use of VR technologies reduces financial costs related to equipment and materials. Simulations eliminate the need for physical materials (Atta et al., 2022; Dhar et al., 2023).	High Costs and Requirements. These technologies are costly. In addition to the expense of hardware, the software and the creation of educational content also require significant investment.

Source: compiled by authors

The prospects for applying VR technologies to modelling complex scientific processes for distance education are promising. Such digital technologies enhance pedagogical capabilities, promote innovative approaches in education, and offer several advantages over traditional teaching methods. However, overcoming the associated challenges will require significant investments in technical infrastructure, updated pedagogical methodologies, and increased digital literacy levels among learners and educators.

Discussion

This article aimed to analyse the potential of virtual reality (VR) in modelling complex scientific processes within the context of distance education. Accordingly, the findings indicate that most selected research studies focused on using VR in higher education, particularly in technical sciences, social sciences, and medicine. It was established that most researchers examined synchronous collaboration among various technologies (including virtual and augmented realities) instead of asynchronous collaboration. The utilisation of VR in distance education within secondary education was represented in 10.8% of publications, while its application in primary education accounted for only 5.0% of the works. Furthermore, only 4.5% of researchers investigated the implementation of virtual reality beyond formal education. The data obtained affirm the trend of understanding VR technologies primarily as opportunities for academic development in a university environment, a perspective highlighted by Al-Ansi et al. (2023) and Antonioli et al. (2014). One may concur, for example, with the conclusions of Austin (2023) and Ikwuka et al. (2024) that the scientific component in secondary schools, even within STEM education, lags behind that of universities. This opinion evidently reflects current trends in pedagogical and scientific advancement in distance education, whereby higher VR technologies are primarily suited for advanced levels of education. Additionally, the results indicate that among the elements related to hardware (devices, types of control) and user interaction with virtual environments (VE), researchers emphasised monitors and displays rather than VR technologies such as head-mounted displays (HMD VR). The use of VR systems for training or therapeutic purposes was less prevalent than for educational objectives (skill formation), which accounted for approximately 25% of the studies. The majority of research concerning the implementation of virtual reality primarily centred on providing virtual environments with various cognitive tasks. Notably, only 28% of the analysed works were theoretical, review, or systematic studies; the remaining 72% consisted of empirical research materials. This aligns with other scholars' conclusions that the results of using virtual reality in distance education should undergo empirical rather than theoretical validation (Aydogan & Aras, 2019; Bingham, 2024; Boichenko et al., 2023; Cejas Martínez et al., 2021). Specifically, the use of structured and semi-structured interviews, surveys, and questionnaires to assess programmes, conduct tests, and perform observations, among other measures, serves as relevant indicators of the effectiveness of distance education employing VR (Ma'ruf et al., 2024).

The results reveal that contemporary research focuses on improving student engagement and developing practical skills within virtual education systems. The motivation of students is also emphasised in scientific studies that discuss the importance of ensuring this metric during the implementation of distance education (Wolf et al., 2020; van der Meer et al., 2023; Smith et al., 2022). However, other scholars have identified that the significance of motivation may be overestimated, as numerous additional challenges can hinder distance learning (Cheng et al., 2021; Cortiz & Silva, 2017; Kljun et al., 2020). Furthermore, the use of VR holds considerable promise in engaging students who are interested in establishing such learning environments. It may be necessary to reassess the motivation of educators, a relatively underexplored issue, given that they bear additional burdens associated with using VR.

The study's proposed results indicate that utilising VR technology holds significant promise. Specifically, these digital solutions enhance the interactivity of learning environments, facilitate personalised education, and enable interdisciplinary studies. They also contribute to reducing financial expenditures on laboratory equipment and reagents while increasing students' engagement in the learning process. The findings corroborate the conclusions of other scholars regarding the vast potential for further integration of AR/VR technologies into the educational process based on distance learning (Daling et al., 2020; de Back et al., 2020; Makhkamova et al., 2020). Some researchers also emphasise that virtual laboratories allow for safe experimentation, particularly when dealing with tasks in atomic physics, medicine, art, chemistry, or when interacting with other hazardous substances (Campisi et al., 2020; Cole et al., 2018; Lichty, 2020). This discussion is valuable from a philosophical standpoint, as it highlights the potential negative psychological effects that digitalisation may have when performing practical tasks.

The challenges associated with the application of virtual reality have also been noted. Such findings align with the conclusions of researchers who recognise existing issues in the development of distance education and propose various solutions for creating comprehensive programmes for the advancement of VR environments (Haleem et al., 2022; Harb, 2019; Hrechanyk et al., 2023). For instance, the cost issue can also be viewed from a different perspective: virtual learning environments allow students from various countries to study without the need for travel to a single location, meaning that some costs that educational institutions would have incurred for purchasing equipment and updating software will automatically shift to the students (Santoveña-Casal & Fernández Pérez, 2020).

At the same time, researchers raise pertinent observations regarding the difficulty of adapting VR to various academic disciplines—the possibility of creating universal software currently does not exist, and developing specialised programmes can be quite costly (Nazarenko, 2015; Malchenko et al., 2020; Raghaw et al., 2018). The lack of standardisation also complicates the overcoming of challenges in using VR in distance education, leading not only to the fragmentation of the educational services market but potentially harming students' health, as emphasised by Liu (2020), Malchenko et al. (2021), and Mladenovic (2020). Clearly, addressing such challenges will require comprehensive solutions and the formulation of holistic strategies. The methodology proposed in the study has certain limitations that warrant attention. Firstly, this pertains to the scholarly literature included in the research. Only English-language publications from peer-reviewed journals or monographic studies published in international journals with the involvement of reviewers were utilised. While this approach allowed for the selection of specialised studies, some non-English publications may have been overlooked. Moreover, despite the positive aspects of this approach, there is a downside: studies published earlier may have been neglected. Such observations do not cast doubt on the relevance of the obtained results but rather open avenues for further analysis of this issue.

Conclusions

The current stage of digitalisation in society has transformed all spheres of life, including education, which is increasingly conducted in a distance format using modern digital solutions, particularly VR technologies. As a result of the conducted analysis, it has been established that researchers primarily focus on the use of VR within higher education systems (across various fields such as technical sciences, social sciences, and medicine) through the lens of synchronous collaboration of different technologies (virtual and augmented reality).

The findings confirm the trend of understanding VR technologies mainly as opportunities for scientific development within the university environment. Among the elements related to hardware (devices, control types) and the ways users interact with virtual environments (VE) (virtual embodiment, degree of virtuality), researchers have emphasised monitors and displays rather than VR technologies such as head-mounted displays (HMD VR).

Certain challenges exist—namely, limitations on the realism of conducting classes, pedagogical and social challenges, and the high costs of equipment and the requirements for its updating. Overcoming these challenges will require comprehensive programmes integrating distance learning with related technologies (including VR).

Promising directions for further research include analysing teachers' motivation when working with VR technologies. Available information indicates the popularity of empirical studies among students. While this approach is entirely valid, it is also important to consider the perspectives on these technologies provided by educators to account for the multifaceted nature of distance learning.

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