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Deep and Interactive Learning in Virtual Simulation Environments: A Review of Assessment Tools, Impacts, and Challenges

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Abstract

Virtual simulation experiments have become a technical means in higher education to simulate the real world to help students acquire skills or experience. They provide a safe and interactive learning environment for students to practice and have been regarded as a beneficial supplementary tool for learning. However, the current virtual simulation experiments still show the gaps between virtual simulation environments and real-world environments. This systematic literature review searched the research articles(2000-2024) across the database of Web of Science, Scopus, and ProQuest, focusing on the deep learning and interactive learning of college students in the virtual simulation environment, aimed to examine the assessment tools for evaluating the students' learning process or outcomes, the findings or impact of virtual simulations on learning outcomes, the specific features of virtual simulation environments contribute to deep and interactive learning and the challenges or limitations of using virtual simulations in higher education. The review pointed out the need to integrate virtual simulation with traditional teaching methods and learning tools to build a multi-dimensional(cognition + behavior + emotion), dynamic(process + result), and cross-environment(virtual + real) system. Educators, technology developers, and assessment experts must work together to upgrade assessment from a judgment tool to part of learning.

Keywords: Deep Learning, Interactive Learning, Virtual Simulation, Assessment, Challenges

Introduction

Experimentation is an essential part of college students' training. Due to the limitations of laboratory space and cost, some important experiments can't be presented and experienced in real scenes. Therefore, virtual simulation experiments have become a technical means in higher education to simulate the real world to help students acquire skills or experience(X. P. Lin et al., 2024). Its most prominent advantage is providing a safe and interactive learning environment for students to practice(Furlan et al., 2021). Therefore, students can repeat experiments, correct mistakes, and conduct flexible learning by interacting with the learning materials(Lee & Noh, 2023). However, there are still gaps between virtual simulation environments and real environments. Most of the current virtual simulation experiments can only provide visual presentation effects of the scene but can't offer tactile interaction(Saini et al., 2024). In addition, a phenomenon has been proposed: some students don't understand the experimental process but only perform mechanical operations in the virtual simulation interface, forming a shallow cognition(Bridge et al., 2015). Therefore, how to effectively use virtual simulation experiments to achieve students' deep and interactive learning and how to measure and evaluate whether students have completed the process and results of deep and interactive learning is necessary.

Deep learning focuses on the construction of knowledge, higher-order thinking, and transfer application(Hobbins et al., 2020). Interactive learning emphasizes human-computer interaction, teacher-student interaction, and student-student interaction(Sun et al., 2022). Deep learning and interactive learning overlap with each other(Jiang, 2022). The achievement of deep learning requires the support of interactive learning. High-quality interactive learning can promote deep learning. This systematic review aims to assess the effectiveness of virtual simulation environments in fostering deep and interactive learning among college students. Accordingly, the research questions are: i: What are the assessment tools for evaluating the students' learning outcomes in the virtual simulation environment? ii: What are the findings or impact of virtual simulations on students' learning outcomes? iii: What specific features of virtual simulation environments contribute to deep and interactive learning for college students? iv: What are the challenges and limitations of using virtual simulations in higher education?

This review is valuable because it synthesizes the current evidence on virtual simulation effectiveness, providing educators and instructional designers with valuable insights into developing and implementing these technologies. As colleges seek to prepare students for an increasingly digital and complex world, understanding how to leverage virtual simulations effectively is crucial for enhancing the quality of higher education.

Methodology

Search Strategy, Including Databases Searched and Keywords Used

The references are from major academic databases, including Web of Science, Scopus, and ProQuest. The search was performed in January 2025. Boolean operators (AND, OR) and truncations were employed to refine the search results. The search formula is as follows:
((“virtual simulat*” OR “virtual lab*” OR “virtual reality simulat*” OR “computer simulat*” OR “digital simulat*” OR “online experiment*”) AND (“deep learning” OR “critical thinking” OR “higher-order thinking” OR “cognitive engagement” OR “meaningful learning” OR “conceptual understanding”) AND (“interactive learning” OR “active learning” OR “collaborative learning” OR “participatory learning” OR “hands-on learning” OR “experiential learning”) AND (“college student*” OR “university student*” OR “higher education” OR “undergraduate*” OR “tertiary education”)).

Inclusion and Exclusion Criteria for Study Selection

The following inclusion criteria were applied to ensure relevance and quality. i: Studies published between 2020 and 2024. ii: Research addressing strategies or implements to enhance deep learning or interactive learning in the virtual simulation environment for

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college students. iii: Studies conducted in educational contexts. iv: Articles providing empirical evidence, including qualitative, quantitative, or mixed-method research. v: Articles published in English.vi: the virtual simulation environment in this review refers to pure virtual simulation, which primarily relies on computer-generated environments to create immersive experiences. It may incorporate additional hardware and interfaces, such as VR, to enhance interactivity and realism.

On the contrary, exclusion criteria included: i: Not a research article but reviews, opinion pieces, editorials, commentaries, the conference paper, and book chapters. ii: Studies don't directly address deep learning or interactive learning in the virtual simulation environment for college students. iii: Articles published in languages other than English.

Process of Study Screening and Selection

Two independent reviewers screened titles and abstracts of identified studies against the inclusion criteria. Full texts of potentially eligible studies were then retrieved and independently assessed by the same reviewers. Any disagreements were resolved through discussion or consultation with a third reviewer.

A standardized form was used to extract relevant data from included studies. Extracted information included: study characteristics (year, country, field), assessment tools, main results, positive features related to the virtual simulation and learning environment, and challenges and limitations of the learning in the virtual simulation environment. Two reviewers independently extracted data, with disagreements resolved through discussion or consultation with a third reviewer. As shown in Fig 1 PRISMA flow diagram, 146 research articles were selected as the objects of this systematic study.

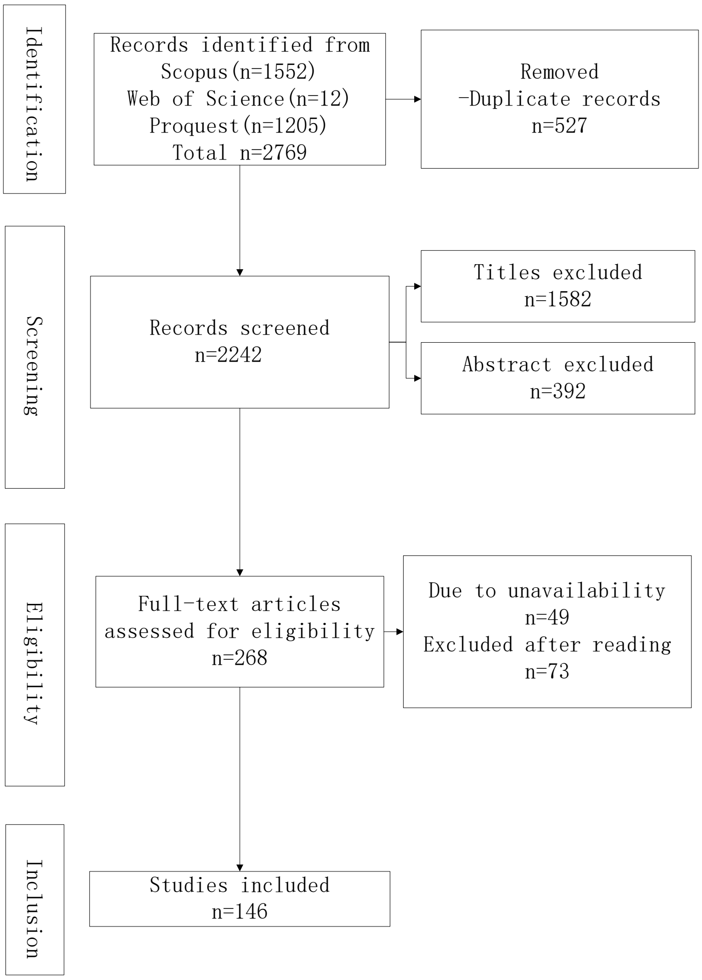

Fig 1 PRISMA flow diagram

Results

Source Characteristics of Included Literature

This review included 16 articles published in 2020, 18 articles in 2021, 28 articles in 2022, 38 articles in 2023, and 46 articles in 2024. The literature came from scholars in different countries, including Arab, Arabia, Australia, Brazil, Brunei, Canada, Chile, etc. Among them, China(29 literature), the United States(21 literature), and Indonesia(10 literature) were the countries with the largest number of articles. As shown in Table 1, the included literature was mostly concentrated in the fields of medical and engineering, followed by physics and chemistry. The number of articles published on learning in the virtual simulation environment showed an upward trend from 2020 to 2024, highlighting increasing global interest and recognition of virtual simulation as an effective educational tool. The research on geographic diversity suggested that education on virtual simulation was global but concentrated in regions with strong technological infrastructure and educational innovation. The virtual simulation covered multiple subject areas but was more popular in hands-on learning scenarios in the natural sciences.

Table 1
The Specific Field of Included Literature

Specific field	The included literature	Number
Medical	(Torda, 2020),(Kimzey et al., 2020),(Thompson et al., 2020),(Nicolaou & El Saifi, 2020),(Shanahan et al., 2021),(Jang & Park, 2021),(Costabile, 2021),(Luctkar-Flude et al., 2021),(Wu et al., 2021),(Gattud et al., 2022),(Fung et al., 2021),(Tsekhmister et al., 2021),(Ros et al., 2021), (Luo et al., 2021),(Abuvatfa et al., 2021),(Dubovi, 2022),(Tee et al., 2022),(Fuoad et al., 2022),(Chang, 2022),(Al-Mugheed et al., 2022),(Qing et al., 2022),(Ibrahem et al., 2022),(Lee et al., 2022),(Musa et al., 2023),(Issleib et al., 2021),(Widiasih et al., 2022),(Chircop et al., 2022),(Sun et al., 2023),(Rodríguez et al., 2023),(Chircop et al., 2023),(Qaisar et al., 2023),(Meng et al., 2023),(Shin & Rim, 2023),(Abdelmoneim et al., 2022),(S. T. Lau, C. J. R. Siah, et al., 2023),(Mäkinen et al., 2023),(Gao & Zhu, 2023),(Serrano-Perez et al., 2023),(Kiegaldie & Shaw, 2023),(Ma et al., 2023),(S. T. Lau, R. C. J. Siah, et al., 2023),(Morais Soares et al., 2023),(Karaduman & Basak, 2023),(Hwang & Chang, 2024),(Zheng et al., 2024),(Chen et al., 2024),(Güngör et al., 2024),(Lee & Baek, 2024),(Huang et al., 2024),(Chang et al., 2024),(P.-H. Lin et al., 2024),(Yang et al., 2024),(Moon et al., 2024),(Jallad et al., 2024),(García-Acosta et al., 2023),(Walls et al., 2024),(Verkuyl et al., 2024),(Liu et al., 2024),(Xuto et al., 2024),(Williams et al., 2024),(Miller et al., 2024),(Chan et al., 2024)	62
Engineering	(Li et al., 2020),(Seifan et al., 2020),(Singh et al., 2021),(Shiradkar et al., 2021),(Verner et al., 2022),(Cook, 2022),(Schnieder et al., 2022),(Huang et al., 2022),(Xin, 2022),(Rahman & Johari, 2022),(Maltais & Gosselin, 2022),(Waskito et al., 2023),(Maxworth, 2023), (Liao et al., 2023),(Jing et al., 2023),(Conesa et al., 2023),(Liao, 2023),(Wang et al., 2024),(Carvalho et al., 2024),(Vahdatikhaki et al., 2024),(Gavitte et al., 2025),(Mathur et al., 2024),(Ismara et al., 2024),(Wong et al., 2024),(Tokatlidis, Tselegkaridis, et al., 2024),(Dewi et al., 2024),(Tokatlidis, Rapti, et al., 2024),(Azzam et al., 2024),(Albarracin-Acero et al., 2024)	29
Chemistry	(Hensen et al., 2020),(Casselman et al., 2021),(Taylor et al., 2024),(P. N. Lau et al., 2023),(Qorbani et al., 2024),(De Lorenzis et al., 2024),(Kolil & Achuthan, 2024),(Bazie et al., 2024)	8
Physics	(Wong et al., 2020),(Swandi et al., 2020),(Hamed & Aljanazrah, 2020),(Yusuf & Widyaningsih, 2020),(Fatmaryanti et al., 2022),(Verawati et al., 2022),(Kim et al., 2022),(Cárdenas-Sainz et al., 2023),(Acevedo et al., 2024)	9
Language	(Chien et al., 2020),(Li et al., 2022),(Y. Wang et al., 2022),(Khodabandeh, 2022),(Li et al., 2023),(Yan et al., 2024),(Wang, 2024)	7
Biology	(Dustman et al., 2021),(Pande et al., 2021),(Savitri et al., 2023),(Navarro et al., 2024),(Tang et al., 2020),(Zamora-González et al., 2024),(Spencer et al., 2024)	7
Management or Business	(Sholihin et al., 2020),(Hernández-Campos et al., 2023),(Kageyama et al., 2022),(Mohd Khalil et al., 2024)	4

Art	(Wu et al., 2023),(Hutson & Olsen, 2022),(Jian & Abu Bakar, 2024)	3
Social work	(Rambaree et al., 2023),(Helle et al., 2023)	2
Science	(Chang et al., 2020),(Lakka et al., 2023)	2
Health	(Kok et al., 2021),(Mørk et al., 2024)	2
Education	(Horváth, 2021),(le Brasseur, 2023)	2
Criminology	(Hurtado-Bermúdez & Romero-Abrio, 2023),(Gerard et al., 2024)	2
Geography and Digital Humanities	(Detyna & Kadiri, 2020)	1
Sports	(N. Wang et al., 2022)	1
Automotive Service	(Makarova et al., 2023)	1
Finance	(Xie et al., 2023)	1
Design	(Banerjee et al., 2023)	1
Computer	(Shadbad et al., 2023)	1
Architecture	(Cao et al., 2024)	1

The Tools Used in the Included Literature to Assess the Effectiveness of Virtual Simulation Environments in Education

As seen from Table 2, questionnaires, tests, scales, and interviews are the most commonly used measurement methods or tools. Few studies used only one of these tools; most studies used various tools to obtain diverse and rich data. Each tool had its advantages and disadvantages. Mixing and using multiple tools or methods could complement each other's strengths and weaknesses. The multiple-choice tests, whether post-test or pre and post-test, were the main tools used to measure students' learning achievement. However, the scenario test, the practical skills exams, and experimental operation evaluation, which combined the virtual simulation experiments and actual experiments, became the potential trend to measure the learning outcomes of virtual simulation(Al-Mugheed et al., 2022; Chang et al., 2024; Gao & Zhu, 2023; Liao et al., 2023; Sun et al., 2023). Compared to the theoretical knowledge test, the scenario test and the practical skill exam could more comprehensively evaluate students' practical ability, deep understanding, and real-world application ability. In addition to knowledge and skills, emotional and motivational factors were also assessed in the virtual simulation environment. For example, the student's engagement was measured through physiological data, precisely heart rate and eye-tracking metrics(Walls et al., 2024). Facial expression analysis was used as the non-invasive way to assess the emotional states(Dubovi, 2022). Those new tools or methods helped educators comprehensively understand students' learning experiences. At the same time, it also represented the innovation and development of educational technology.

Table 2
Summary of Assessment Methods or Tools Used in the included literature

Assessment Method/Tool	Purpose	Frequency of Use	Advantages	Limitations
Questionnaire	Both qualitative and quantitative feedback	90	Cost-effective	Limited depth
Test, or Pre- and Post-tests	Measure knowledge acquisition	79	Quantifiable results	Focus on theoretical knowledge
Likert scale	Measure students' satisfaction,engagement, and other things	46	Scalable and easy to analyze	Subjective responses
Interviews	Gather qualitative feedback	28	Rich, detailed insights	Time-consuming
Experimental or task Reports	Document students' interactions, decisions, or outcomes	7	Comprehensive Feedback	Interpretation Complexity
Log files	Provide records of interactions within the system	6	Objective Data	Technical Limitations
Observation sheet	Assess a wide range of performance	5	Holistic view	Observer Bias
Rubric	Clarify Expectations and promote consistency	5	Efficient Grading	Overemphasis on quantification
Checklist	Process Standardization	4	High Efficiency	Rigidity
Debriefing sessions	Facilitate description and reflection on past experiences	3	Encourage Reflection	Depends heavily on the facilitator's competence
Practical skills exam	Assess applied skills	2	Focus on hands-on performance	Resource intensive
Scenario test	Practice and demonstrate skills	2	Risk-Free Environment	Limited realism
Facial Expression Analysis	Emotion Detection	1	Non-invasive way to assess emotional states	Technical challenges
Experimental Operation Evaluation	Comprehensive Assessment	1	Combine the Virtual simulation experiments and actual experiments	Resource intensive
Physiological Parameters measurement	Measure students' engagement through physiological data	1	Objective data	Technical and cost challenges
Field Notes	Provide records of what occurred	1	Rich and flexible record	Subjectivity or bias

The Main Findings or Impact of Virtual Simulations on Students' Learning Outcomes

The positive features related to the virtual simulation environment can be seen in Table 3, and the findings associated with deep learning and interactive learning can be seen in Table 4. Overall, the literature was positive for deep learning and interactive learning results in virtual simulation environments. Firstly, virtual simulation experiments help students understand complex concepts more deeply through visualization and interactive operations while improving problem-solving skills and critical thinking(Casselman et al., 2021; Cook, 2022; Helle et al., 2023; Maltais & Gosselin, 2022; Maxworth, 2023; Shanahan et al., 2021). Secondly, the instant feedback and repeatable operating environment provided by virtual simulation experiments provide reflective learning support for students(Chang et al., 2024; Hwang & Chang, 2024; P. N. Lau et al., 2023; Xuto et al., 2024). In addition, the technical characteristics of virtual simulation experiments, such as immersion and interactivity, further enhance students' learning experience and engagement(Bazie et al., 2024; Hensen et al., 2020; Kimzey et al., 2020; Li et al., 2020; Tang et al., 2020). Overall, virtual simulation experiments have shown the potential to promote deep and interactive learning.

However, the literature showed that it should be regarded as the result of the combined action of multiple factors rather than relying solely on the virtual simulation itself. For example, Inquiry-based learning, blended learning, or collaborative learning, as a combination of approaches, was integrated into the learning process of virtual simulation experiments(Chang et al., 2020; Chien et al., 2020; Huang et al., 2024; Hwang & Chang, 2024; Makarova et al., 2023; Meng et al., 2023; Prasad, 2021; Rahman & Johari, 2022; Rambaree et al., 2023; Shadbad et al., 2023; Swandi et al., 2020; Wong et al., 2020; Xie et al., 2023). Similarly, the instructor's observations, evaluations, on-site tutoring, coaching, and feedback were indispensable for students' reflection and improvement(Fung et al., 2021; Tsekhmister et al., 2021; Xie et al., 2023; Yan et al., 2024; Yusuf & Widyaningsih, 2020). At the same time, it was also inseparable from the active exploration of students(Gavitte et al., 2025; Tokatlidis, Rapti, et al., 2024).

Table 3
Positive features of virtual simulation learning environments

Positive features	Description	Representative literature
Usability and Ease of Use	Students can operate the system interface, and the learning tasks are clear and specific.	(Wong et al., 2020),(Costabile, 2021),(Conesa et al., 2023),(Mørk et al., 2024)
Immediate Feedback	Provide real-time feedback to help students reflect on their mistakes and practice again.	(Casselman et al., 2021),(Abdelmoneim et al., 2022),(Liu et al., 2024),(Xuto et al., 2024)
Safe and controlled environment	With no harm to humans, no damage to equipment or the environment, and precise experimental control conditions.	(Morais Soares et al., 2023),(le Brasseur, 2023),(Chen et al., 2024),(Xuto et al., 2024)
Visual and interactive feature	Visually presenting learning content and allowing manipulation and exploration of	(Zheng et al., 2024),(Qorbani et al.,

	virtual objects to enhance the immersion and engagement of the learning experience.	2024),(Acevedo et al., 2024),(Jallad et al., 2024)
Flexibility in individual learning	Learn at one's own pace and in one's way, and adjust learning strategies through repeated practice.	(Verawati et al., 2022),(Kiegaldie & Shaw, 2023),(Helle et al., 2023),(Wang, 2024)
Real-world and practical contexts	Real-world contexts can stimulate students' learning interest and motivation, and promote critical thinking and problem-solving skills.	(Wang, 2024),(Cao et al., 2024),(Spencer et al., 2024),(Dewi et al., 2024)
Cost-effective alternative	Eliminate the need for physical materials and space, especially when physical laboratories are unavailable.	(Tokatlidis, Tselegkaridis, et al., 2024),(Bazie et al., 2024)

Table 4
The findings related to deep learning and interactive learning

Learning dimension	Study results	Representative literature
Associated with Deep Learning	Deeper understanding of concepts	(Wong et al., 2020),(Sholihin et al., 2020),(Swandi et al., 2020),(Casselman et al., 2021)
	Developed problem-solving skills	(Li et al., 2020),(Shanahan et al., 2021),(Dustman et al., 2021),(Chang, 2022)
	Developed critical thinking	(Li et al., 2020),(Chien et al., 2020),(Chang et al., 2020),(Dustman et al., 2021)
	Longer retention of topic knowledge	(Pande et al., 2021),(Shiradkar et al., 2021),(Al-Mugheed et al., 2022),(Meng et al., 2023)
	Facilitation of integrative thinking of the entire system	(Verner et al., 2022)
	Improvement in reasoning and decision-making skills	(Verawati et al., 2022),(Abdelmoneim et al., 2022),(Gao & Zhu, 2023),(Morais Soares et al., 2023)
	More self-regulation	(Wu et al., 2023)
	Improvement in Meta-cognitive awareness	(Yusuf & Widyaningsih, 2020),(Wu et al., 2023),(Li et al., 2023)
Associated with Interactive learning	Higher engagement	(Torda, 2020),(Li et al., 2020),(Detyna & Kadiri, 2020),(Luctkar-Flude et al., 2021)

	Increase in empathy	(Kimzey et al., 2020),(Rambaree et al., 2023),(García-Acosta et al., 2023)
	Increased responsibility	(Dustman et al., 2021)
	Improved communication skills	(Tee et al., 2022),(García-Acosta et al., 2023),(Williams et al., 2024)
Associated with deep and interactive learning	Improved test scores	(Chang et al., 2020),(Costabile, 2021),(Wu et al., 2021)
	Improved professional skills	(Chien et al., 2020),(Jang & Park, 2021),(Fung et al., 2021),(Abuvatfa et al., 2021)
	Enhanced self-directed learning abilities	(Tsekhmister et al., 2021),(Lakka et al., 2023)
	Higher satisfaction	(Tsekhmister et al., 2021),(Luo et al., 2021),(Chang, 2022),(Lee et al., 2022)
	Improved learning interest and motivation	(Wong et al., 2020),(Chien et al., 2020),(Chang et al., 2020),(Detyna & Kadiri, 2020)
	Enhanced self-efficacy	(Chang et al., 2020),(Kiegaldie & Shaw, 2023),(Shadbad et al., 2023),(Moon et al., 2024)
	Enjoyable or positive learning experience	(Costabile, 2021),(Fung et al., 2021),(Pande et al., 2021),(Hutson & Olsen, 2022)
	More confidence	(Wu et al., 2023),(Schnieder et al., 2022),(Widiasih et al., 2022),(Chircop et al., 2023)

Challenges and Limitations of Virtual Simulation Environments

Despite virtual simulation's positive features and advantages, there were limitations and challenges summarized in Table 5. In response to these challenges and limitations, future research can be carried out from the following aspects. The first is technological innovation, which means developing more advanced multi-sensory feedback devices (such as tactile gloves, olfactory simulators, etc.) to enhance the immersion of virtual environments, optimize the realism of virtual environments, and lower the technical threshold of hardware and software, develop lighter and more compatible virtual simulation devices. On the other hand, explore open source platforms and modular designs to reduce virtual simulation systems' development and maintenance costs. The second aspect is to improve teaching design. Design teaching content and activities that align with the characteristics of the virtual environment to fully utilize the advantages of virtual simulation. Develop a hybrid learning model that organically combines virtual simulation with traditional teaching methods to compensate for their shortcomings. Provide teacher training and technical support to help educators use virtual simulation technology better. In particular, teachers should evaluate students' learning outcomes and provide personalized feedback through data analysis and technology (such as artificial intelligence) or develop standardized assessment tools and methods to measure students' learning outcomes in virtual environments more accurately.

Table 5
The Challenges/ Limitations of Virtual Simulation Environments for Learning

Challenges/ Limitations	Description	Representative literature
User physical discomfort	Physical discomfort of dizziness or cybersickness.	(Abdelmoneim et al., 2022),(S. T. Lau, R. C. J. Siah, et al., 2023),(Liao et al., 2023),(Azzam et al., 2024)
Limited sensory experience	It mainly focuses on vision or hearing and lacks other senses.	(Wong et al., 2020),(Serrano-Perez et al., 2023),(Acevedo et al., 2024),(Tokatlidis, Rapti, et al., 2024)
Limited realism scenarios	Simplified or idealized models of real-world systems don't capture all the complexities.	(Sholihin et al., 2020),(Qaisar et al., 2023),(Waskito et al., 2023),(Mäkinen et al., 2023)
Technological barrier	Hardware limitations, software compatibility, and internet connectivity.	(Meng et al., 2023),(Cárdenas-Sainz et al., 2023),(Gao & Zhu, 2023),(Jing et al., 2023)
Low-quality immediate feedback	Simple feedback lacks details, context, or relevance.	(P.-H. Lin et al., 2024),(Zamora-González et al., 2024),(Yang et al., 2024),
Development and maintenance costs	Creating high-quality virtual simulations requires a lot of resources and may lead to educational inequities.	(Banerjee et al., 2023),(Morais Soares et al., 2023),(Liao, 2023),(Vahdatikhaki et al., 2024)
Social interaction limitations	Mainly human-computer interaction, and lack of face-to-face human interaction.	(Musa et al., 2023),(Maltais & Gosselin, 2022),(Abdelmoneim et al., 2022),(Gerard et al., 2024)
Implementation and integration with traditional methods and education	Virtual simulations often involve knowledge from multiple disciplines, while traditional methods may rely on domain-specific knowledge.	(Morais Soares et al., 2023),(Li et al., 2023),(Hwang & Chang, 2024),(Mohd Khalil et al., 2024)
Assessing students' learning in virtual simulation environments	Virtual simulations may focus on technique or procedure but neglect soft skills.	(Ibrahem et al., 2022),(Savitri et al., 2023),(Bazie et al., 2024)

Discussion

Virtual Simulation is a Beneficial Supplementary Educational Tool for Deep and Interactive Learning but Can't Replace Real Experiments

The literature results affirmed the positive features of virtual simulation experiments and their roles in promoting deep learning and interactive learning, but they also pointed out their limitations and challenges. Virtual simulation experiments can't replace real experiments, but they are a beneficial supplementary tool for higher education and complement traditional teaching(Chircop et al., 2022; Seifan et al., 2020; Serrano-Perez et al., 2023). Based on the features and findings shown in Table 3 and Table 4, it is recommended that instructors use virtual simulations for theory reinforcement and pre-lab training while retaining physical laboratories for skill development. Especially in the digital era, when students have the conditions to conduct self-directed learning, virtual simulation experiments can be opened to junior students.

To better play the supplementary role of virtual simulation experiments, future research can focus on the following directions. First, explore how to organically combine virtual simulation experiments with traditional teaching methods or other learning tools, such as AI technology, to maximize educational effects. Second, reduce the development and use costs of virtual simulation experiments through technology optimization and resource sharing so that they can be more widely used in higher education. Third, relevant training for teachers is provided to help them effectively use virtual simulation experiments; at the same time, technical support is offered to students to ensure they can smoothly adapt to the new learning environment.

There are different learning experiences of virtual simulation experiments in various disciplines. Virtual simulation experiments are more effective in the field of natural sciences than in other fields

Virtual simulation experiments use technical methods to simulate real-world scenarios and processes, but the degree of replication varies depending on the level of technology and application areas. As summarized in Table 1, virtual simulation experiments are widely used in fields such as medicine, engineering, and physics but are less used in fields such as management and business. In the medical field, students need many operational skills, such as surgery and nursing skills, and engineering and physics fields also involve equipment use and experimental operations. The learning contents in these fields usually have clear processes and rules(Lakka et al., 2023; Mäkinen et al., 2023; Rodríguez et al., 2023; Shin & Rim, 2023; Wong et al., 2020). Virtual simulation experiments can highly replicate these processes, provide a safe and repeatable operating environment, and help students understand and master these processes and skills. However, management focuses more on soft skills, such as leadership, and business learning involves complex market environments and interpersonal relationships(Kageyama et al., 2022; Mohd Khalil et al., 2024; Sholihin et al., 2020). Those contents are highly uncertain and subjective and difficult to replicate accurately through virtual simulation experiments.

Actually, in addition to simulating the real world, virtual simulation experiments can provide other unique learning experiences. First is interdisciplinary and systems thinking. Virtual simulation can integrate knowledge from different disciplines into one scenario, design virtual simulations based on real problems, and allow students to use interdisciplinary knowledge to solve complex problems, thus breaking disciplinary boundaries. It can help students develop systematic thinking, integrate knowledge from different courses and disciplines, and prepare for physical laboratory work and real scenes(Verner et al., 2022). Second, virtual simulation can set up extreme scenarios, such as polar expeditions, super typhoons, infectious disease transmission and disposal, and deep-sea microbial sampling, allowing students to exercise their resilience and decision-making abilities in a consequence-free environment, stimulating their imagination and creativity.

Virtual simulation experiments are highly consistent with the ideas of constructivist learning theory and strengthen its core ideas in the virtual simulation environments

Constructivist learning theory advocates that learners play an active role in knowledge construction, believing that knowledge is not passively accepted but actively constructed through the interaction between individuals and the environment(Bada & Olusegun, 2015). Virtual simulation aligns well with constructivist learning theories, promoting experiential learning through simulated real-world situations, which allows students to apply theoretical knowledge in practice. This experiential learning is a core principle of constructivism, as students construct their understanding through real-world applications. Virtual simulation also provides students with interactive scenarios, allowing them to operate and explore independently and choose a learning method based on their pace and interests(Serrano-Perez et al., 2023). It allows students to make mistakes and gives them the opportunity to reflect and correct their mistakes(Shin & Rim, 2023). Some virtual simulation experiments also support multi-person collaboration. Students can play different roles in the virtual environment and solve problems together to interact with others. Therefore, virtual simulation experiments fully implement the core principles of constructivist learning theory.
However, due to the limitation of deep feedback and social interaction from the virtual simulation, teachers' guidance, support, and encouragement in this student-centered learning process are also very important(Lakka et al., 2023; Moon et al., 2024). Compared with traditional lecture classrooms, virtual simulation experimental classrooms require more instructors to supervise and guide and tend to have smaller class sizes(Mørk et al., 2024). Without proper guidance and support, VR may not yield the desired learning outcomes(Detyna & Kadiri, 2020).

For the students, virtual simulation environments can be a catalyst for their construction process, but they must serve the goal of active learning. Virtual simulation accelerates the knowledge construction process through interactivity (such as dragging experimental equipment), instant feedback (such as error prompts), and situational immersion (such as VR operating room). However, technology itself doesn't directly generate knowledge and needs to rely on the active participation of learners (such as thinking, trial and error, and reflection)(Torda, 2020; Wu et al., 2023; Yusuf & Widyaningsih, 2020). The results of virtual simulation experiments shouldn't be evaluated based on whether students have operated the experiment but on whether they have raised new questions or revised their original cognition. In other words, learning must retain cognitive initiative.

The new trend of multi-dimensional, dynamic, and cross-environment systems for daily learning assessment in virtual simulation environments

Table 2 shows various tools that are usually used in the included literature to evaluate students' learning outcomes for research purposes. Typically, the sample size of students in educational research was limited, and researchers invested a lot of time and energy in it(Hwang & Chang, 2024; Sholihin et al., 2020). However, in daily teaching, teachers may need to face many students and have limited time for learning evaluation. Therefore, how to assess the deep and interactive learning results still faces limitations and challenges in daily life. Although the existing virtual simulation system can record students' operation data, it can't analyze students' thinking logic and effectively capture high-level abilities such as critical thinking and knowledge transfer. Moreover, in different fields, the evaluation indicators of each system are fragmented and lack a unified framework. For example, oral language training focuses on pronunciation parameters, and medical experiments focus on operational specifications(Rodríguez et al., 2023; Wang, 2024).

The assessment of deep learning and interactive learning in a virtual simulation environment needs to build a multi-dimensional(cognition + behavior + emotion), dynamic(process + result), and cross-environment(virtual + real) system, which requires educators, technology developers, and assessment experts to work together to upgrade assessment from a judgment tool to part of learning. As summarized in Table 2, limited literature focuses on measuring psychological, emotional, or cross-context learning outcomes. Those measurement tools are not widely used due to technology, labor, or financial costs. As technology is gradually promoted, these tools may be commonly used in comprehensive, process-based, and long-term learning outcome measurement.

Conclusion

This review synthesizes the current state of deep and interactive learning in virtual simulation environments. It summarizes the assessment tools for evaluating the students' learning outcomes and key findings, features of virtual simulation environments that contribute to deep and interactive learning for college students, and their limitations and challenges. This research integrates deep learning and interactive learning in the virtual simulation environments into a unified framework, filling the gap in the existing literature review on the comprehensive effect of deep learning and interactive learning in virtual environments. It shows that virtual simulation environments have significant potential to promote deep learning and interactive learning among college students. However, pure technical presentation can't automatically trigger deep and interactive learning. Scientific teaching design, precise measurement, and dynamic evaluation are essential elements.

The future development of virtual simulation should not only focus on its technological level, such as higher human-computer interaction and authenticity of the scenarios, but also must break through the potential gaps in student learning outcomes, such as shallow cognition and empty social interaction. In addition to instructors' actual participation and perception, multi-dimensional(cognition + behavior + emotion), dynamic(process + result), and cross-environment(virtual + real) assessment systems can be developed to track the learning process and results. Future research work should investigate the longitudinal effects of virtual simulation learning on hybrid assessment models combining AI or other scientific tools. Educators, technology developers, and assessment experts must work together to upgrade assessment from a judgment tool to part of learning.

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