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Virtual simulation experiments in medical education: technology acceptance, learning outcomes, and motivational impacts

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Abstract

Background Virtual Simulation Experiments (VSE) are increasingly applied in medical education, yet their role in medical microbiology remains underexplored. This study evaluated a VSE system designed for the isolation, culture, and identification of enteric pathogens, framed by Self-Determination Theory (SDT) and the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2).

Methods Ninety medical students were randomly assigned to either a VSE group or a traditional teaching group. Outcomes were assessed through operational skill and knowledge tests, supplemented by qualitative feedback.

Results The VSE group achieved higher scores in operational skills (89.6 ± 5.2 vs. 81.8 ± 6.3 , $p < 0.01$) and knowledge retention (87.4 ± 4.4 vs. 81.8 ± 5.0 , $p < 0.01$). Students reported that VSE immersive environment and instant feedback enhanced satisfaction and autonomy, aligning with SDT.

Conclusions VSE significantly improved learning outcomes in medical microbiology and promoted intrinsic motivation. These findings provide empirical support for integrating VSE into medical curricula and highlight the need for further research on its long-term and broader educational impact.

Keywords Virtual simulation experiment, Medical education, Self-Determination theory, Learning motivation, Skill mastery

Introduction

Virtual Simulation Experiments (VSE) represent an innovative, student-centered pedagogical approach that integrates digital technology with Virtual Reality (VR), thereby providing a transformative platform for experiential learning in medical education [1, 2]. This immersive educational paradigm enhances student motivation and engagement, while offering a more flexible and dynamic

learning experience compared to traditional methods [3–5].

Despite the increasing application of VSE across various medical disciplines, its implementation in medical microbiology—a crucial field for understanding infectious diseases and developing foundational laboratory diagnostic skills—remains underexplored. This gap in the literature is noteworthy, as medical microbiology education requires innovative teaching strategies to effectively communicate complex concepts and foster practical skills within a safe and controlled environment [6, 7].

However, the successful integration of VSE into the curriculum remains a multifaceted challenge. Its effectiveness cannot be assessed solely on the basis of skill

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improvement. It is critically contingent upon two intertwined dimensions: the student's intrinsic motivation to engage with the learning process, and their acceptance of the technology itself. A pedagogically sound VSE that students are unwilling to use is as ineffective as a technologically sophisticated tool that fails to promote deep learning. Therefore, a comprehensive evaluation framework is essential to understand this complex interplay.

To address this gap, this study develops a novel analytical framework by integrating two robust theories: Self-Determination Theory (SDT) and the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2). SDT provides a lens through which to examine the internal psychological factors that drive student motivation and engagement, particularly the needs for autonomy, competence, and relatedness. In parallel, UTAUT2 offers a framework for analyzing the external determinants influencing students' behavioral intentions to adopt and utilize new technologies, such as perceived usefulness and ease of use. By combining these two perspectives, we aim to offer a holistic understanding of VSE's educational impact.

The primary objective of this study is to systematically assess the effectiveness of the custom-designed VSE system for medical microbiology education. We investigate its impact on students' operational skill acquisition, knowledge retention, and learning motivation within the integrated SDT-UTAUT2 framework. The findings are intended to provide empirical evidence for educators and instructional designers, yielding insights into how VSE systems can be designed and implemented to be not only technologically accepted but also motivationally engaging.

Literature review

The role and challenges of VSE in medical laboratory education

The acquisition of proficient laboratory skills is a cornerstone of medical education, particularly in disciplines such as microbiology, hematology, and clinical chemistry. Traditional laboratory teaching, while essential, faces challenges such as limited access to equipment, safety concerns with pathogenic materials, high costs of consumables, and difficulties in providing individualized, repeatable practice opportunities for large student cohorts [8]; VSE has emerged as a promising solution to these challenges. It provides a safe, scalable, and resource-efficient platform where students can repeatedly practice complex procedures, such as bacterial staining, culture inoculation, and biochemical identification, without real-world risks or limitations [9–11]. Research has demonstrated that VSE can effectively replicate complex clinical scenarios and practical procedures, enhancing students' proficiency in fundamental skills [12–14].

However, much of the existing research focuses on procedural fidelity and skill outcomes, often overlooking the critical psychological and technological factors that underlie student engagement and learning. Furthermore, there is a specific scarcity of research examining VSE within the context of foundational medical sciences such as microbiology [15, 16].

A theoretical framework for understanding VSE impact

To develop a holistic understanding of VSE's effectiveness, it is essential to move beyond simple pre-post test designs and examine the underlying mechanisms of learning and technology adoption. We propose an integrated framework grounded in SDT and UTAUT2.

Intrinsic motivation through SDT

SDT is a prominent macro-theory of human motivation concerned with the development and functioning of personality within social contexts [17]. SDT posits that optimal human functioning and intrinsic motivation are fostered when three basic psychological needs are met: autonomy, competence, and relatedness.

- Autonomy refers to the need to feel a sense of volition and self-endorsement in one's actions. In a VSE environment, autonomy can be supported by allowing students to learn at their own pace, repeat difficult steps without penalty, and explore different outcomes, thereby fostering a sense of ownership over their learning [18].
- Competence is the need to feel effective and capable in one's interactions with the environment. VSE systems can directly nurture competence by providing structured guidance, immediate, risk-free feedback on errors, and clear indicators of progress, which helps students build confidence and mastery [19].
- Relatedness involves the need to feel connected to and cared for by others. While often seen as a challenge in virtual environments, VSE can incorporate features that promote relatedness, such as collaborative tasks or integration with instructor feedback loops, though this aspect is often less explored.

By applying SDT, we can analyze how specific design features of a VSE system satisfy these psychological needs to enhance students' intrinsic motivation, which is a powerful predictor of deep learning and sustained engagement.

Technology acceptance through UTAUT2

While SDT explains the motivational pull of a learning activity, UTAUT2 explains the factors that influence an individual's intention to use a new technology [20]. UTAUT2 is a leading model in information systems research and is highly relevant for understanding why students choose to engage with-or resist-educational technologies like VSE. Key constructs include:

- **Performance Expectancy:** The degree to which an individual believes that using the system will help them attain gains in job performance (in this context, academic performance).
- **Effort Expectancy:** The degree of ease associated with the use of the system.
- **Social Influence:** The degree to which an individual perceives that important others (e.g., instructors, peers) believe they should use the new system.
- **Facilitating Conditions:** The degree to which an individual believes that an organizational and technical infrastructure exists to support the use of the system.

UTAUT2 provides a structured framework to assess the external factors and user perceptions that drive the adoption of VSE, complementing SDT's focus on internal motivation.

The integrated framework and the present study

The innovation of our study lies in the synthesis of SDT and UTAUT2. This integrated framework posits that for a VSE to be truly effective, it must not only be perceived as useful and easy to use (UTAUT2) but must also fulfill students' fundamental psychological needs for autonomy and competence (SDT). This dual perspective allows us to address a significant gap in the literature, which often examines educational technology through either a purely pedagogical or a purely technological lens. This study, therefore, is among the first to use this integrated model to comprehensively examine the impact of VSE in the critical domain of medical microbiology education.

Methodology

Participants

The participants in this study were second- and third-year students from a medical university in China. A total of 102 questionnaires were distributed, resulting in 90 valid responses, which yields a response rate of 88.2%. Among the participants, 40 were male (44.4%) and 50 were female (55.6%), with the majority studying medical laboratory technology and clinical medicine. To ensure balance in the sample, the gender and grade distribution were approximately equal between the experimental and control groups.

The selection criteria for participants were based on their enrollment in relevant medical laboratory courses, particularly those involving experimental procedures in medical microbiology. The sample included both students who were using VSE for the first time and those with prior experience, allowing for a comprehensive assessment of the impact of VSE.

The virtual simulation experiment (VSE) system and pedagogical design

The VSE system serves as a platform that provides immersive and interactive learning experiences for complex experimental scenarios in medical education. The system used in this study was a bespoke software solution developed in-house by our university's technical team in collaboration with microbiology faculty, ensuring alignment with curricular objectives. A visual overview of the system's interface, key operational steps, and workflow is provided in Fig. 1. This system enables students to simulate critical medical procedures in a virtual environment, facilitating the mastery of skills that are difficult to replicate or pose high risks in real-life settings, such as clinical simulations and experimental operations. In this study, our VSE system is specifically employed to simulate the isolation and identification of enteric pathogens, utilizing virtual reality technology to deliver intuitive and structured operational workflow. Students are guided through each essential step within the virtual environment, including sample inoculation, microscopic observation, medium selection, biochemical reactions, serological tests and other diagnostic procedures.

The pedagogical structure of the VSE experience was designed based on Kolb's Experiential Learning Cycle [21], guiding students through four distinct phases: Concrete Experience, Reflective Observation, Abstract Conceptualization, and Evaluation and Revision.

Concrete experience

During the concrete experience phase, students engage with the simulation environment through the virtual experiment system, completing designated experimental procedures in an immersive manner. The system employs high-precision 3D modeling to illustrate the steps involved in isolating enteric pathogens, including media preparation, sample inoculation, bacterial morphology observation, and serological testing. Students can adjust their viewpoint at any time during the experiment to closely examine every detail. For instance, when inoculating a sample, the system provides operational feedback that replicates the actual technique of marking zones in real-life procedures. This allows students to practice the operation repeatedly, ensuring the accuracy and fluidity of their actions. This approach not only enhances students' proficiency in experimental techniques but also

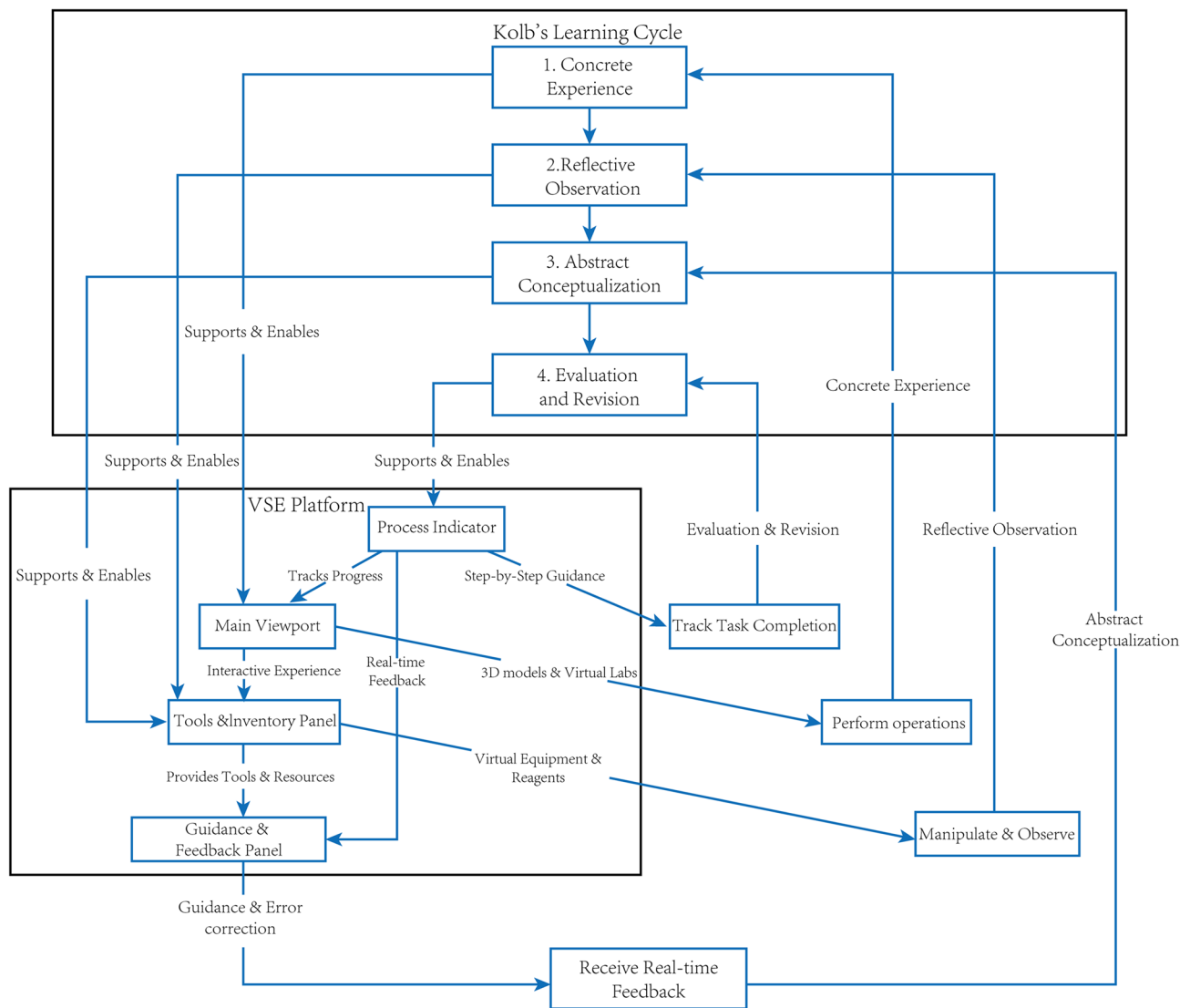


Fig. 1 Integration of Virtual Simulation Experiments (VSE) with Kolb's Experiential Learning Cycle, framed by SDT and UTAUT2. Legend: The VSE platform aligns with Kolb's four stages: (1) Concrete Experience through simulated microbiology labs, (2) Reflective Observation via system feedback, (3) Abstract Conceptualization linking practice to theory, and (4) Active Experimentation in repeated simulations. This process is grounded in SDT (motivation) and UTAUT2 (technology acceptance), providing a unified framework for medical education

intuitively supports their understanding of the experimental processes.

Reflective observation

In the reflective observation phase, the system encourages students to explore the details of the experimental procedures through guiding questions. After completing each step, the system automatically generates prompts that require students to reflect on the accuracy of their operations and the significance of the experimental results. For instance, after conducting microscopic observations of bacterial morphology, the system may pose questions such as, "What are the morphological characteristics of this bacterium? How can it be distinguished from other bacteria?" This question design fosters deep

thinking during observations and reinforces students' understanding of experimental concepts.

Additionally, students can utilize the system's "recording function" to document their observations and reflections, which can subsequently be incorporated into their experimental reports. This process cultivates critical thinking and self-correction skills in experimental contexts, enabling students to continuously refine their operational competencies.

Abstract conceptualization

Following the experimental operations and reflective observations, students enter the abstract conceptualization phase. In this stage, they are required to transform specific operational activities from the experiment into

abstract theoretical knowledge and compile a comprehensive experimental report. The system provides guidance for reviewing experimental steps and theoretical frameworks, assisting students in organizing the content of their reports. During this phase, students must detail their operational processes while also analyzing their results in conjunction with theoretical concepts from their coursework. For instance, they may discuss how the choice of media used in the experiment influences bacterial growth and analyze discrepancies in biochemical reaction results. This process facilitates the integration of practical operations with theoretical knowledge, thereby enhancing their analytical skills and theoretical understanding.

Evaluation and revision

The evaluation and revision phase culminates with feedback on the experimental report and self-assessment. The system offers immediate feedback, highlighting shortcomings or errors in the reports. Students can revise their work based on this feedback, correcting errors in experimental data or supplementing their analyses of experimental phenomena. Additionally, the system automatically checks for errors and formatting issues to ensure professionalism. Through this feedback mechanism, students can continuously optimize their experimental skills and report-writing abilities. This not only improves their operational proficiency but also cultivates a rigorous scientific attitude and enhances their competence in report writing.

Experimental procedure

This experiment employed a controlled design to compare the effects of VSE with traditional teaching methods on student learning outcomes. Participants were randomly assigned to two groups: the experimental group learned using the VSE system, followed by hands-on experiments on the isolation and identification of enteric pathogens, while the control group was instructed through conventional laboratory methods. The experiment lasted six weeks, with students completing one laboratory task each week. Data was collected at three primary time points: a pre-test at the beginning of Week 1, an immediate post-test at the end of Week 6, and a knowledge retention post-test two weeks after the conclusion of the experiment (Week 8).

The VSE system provided students with a highly interactive virtual laboratory environment, allowing them to repeat procedures multiple times to ensure mastery of the experimental steps. Additionally, the system offered immediate feedback on each critical operational step, facilitating quick corrections of errors and boosting students' confidence in their abilities. This combination of interactivity and instant feedback empowered students to

autonomously enhance their performance and increased their motivation to engage in the experiments. Compared to traditional methods, the VSE's immediate feedback mechanism not only improved the precision of experimental procedures but also reduced error rates and feelings of anxiety, further enhancing students' motivation and engagement.

Prior to the commencement of the experiment, all participants received appropriate training to familiarize them with the processes and procedures involved. At the conclusion of the experiment, students completed a post-test to assess their operational skills, knowledge retention, and learning motivation.

Measuring tools

The measurement tools used in this study, including several questionnaires, were developed by the research team. The development process involved a comprehensive review of relevant literature, initial item pool generation, and content validation by a panel of three senior medical education experts. A pilot study with 30 students was conducted to refine item wording and ensure clarity. The internal consistency reliability for each scale was assessed using Cronbach's alpha (α), with results reported below. The full questionnaires and scoring rubrics are available as Supplementary Material 1.

Composition evaluation scale Students' operational skill performance was assessed not through self-report measures, but via direct evaluation by two independent instructors using the Composition Evaluation Scale, a detailed scoring rubric (inter-rater reliability, Cohen's Kappa = 0.85; Cronbach's alpha = 0.88). This rubric-based observation protocol enabled the quantitative assessment of performance in experimental procedures, with emphasis on the accuracy, efficiency, and autonomy of students' actions. The scoring range for this scale was 0–100 points, divided into four dimensions: correctness of experimental procedures (35%), fluency of experimental steps (35%), flexibility and adaptability in operations (20%), and independence and decision-making ability (10%).

Learning behavior engagement questionnaire The Learning Behavior Engagement Questionnaire employs a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) to assess students' motivation and engagement during experiments (Cronbach's α = 0.85). It covers aspects such as participation level, attentiveness, post-experiment reflection, and peer interaction.

Learning experience interview questionnaire To gather qualitative feedback on students' experiences with the VSE system, learning experience interviews were conducted with a purposive sample of 12 students from the

experimental group. These participants were selected based on their performance in the VSE experiments (six high performers and six students who encountered performance challenges), ensuring a comprehensive range of perspectives.

Each interview, conducted in the week following the six-week experiment, lasted approximately 20–30 min and followed a semi-structured protocol (see Supplementary Material 2). To ensure that participants felt comfortable speaking openly and candidly about their course experiences without the potential anxiety of being recorded, audio recordings were deliberately avoided. Instead, a rigorous note-taking protocol was implemented: the lead researcher documented detailed notes and captured verbatim quotations during the interviews. Immediately after each session, the researcher expanded upon these notes, adding contextual details and reflections while the memory was still fresh. These comprehensive field notes served as the primary data for the subsequent thematic analysis.

The interviews aimed to assess students' satisfaction and gather insights into their experiences with the system. Key guiding questions included: "How did the VSE system enhance your experimental skills?" "What challenges did you encounter while using the VSE system?" "What is your overall impression of using VSE for experiments?" and "Would you recommend VSE to your classmates?"

Study habit questionnaire The Study Habit Questionnaire assesses students' study behaviors, including self-management skills, time allocation, and focus during study sessions (Cronbach's $\alpha = 0.81$). It contains five items that explore students' daily learning activities, such as "How much time do you spend reviewing lessons each day?" and "Do you prepare in advance for experimental operations?" This questionnaire helps analyze the relationship between study habits and experimental performance. An overall study habit score for each student was calculated by averaging their responses to the five items.

Data analysis

Quantitative data were analyzed using SPSS Version 26.0. Independent samples t-tests were used to compare the mean scores of the experimental and control groups. Pearson correlation analysis was conducted to examine the relationship between student engagement and experimental outcomes. A p -value of < 0.05 was considered statistically significant.

Qualitative data from the semi-structured interviews were transcribed verbatim and analyzed using a thematic analysis approach [22]. The process involved two researchers independently reading the transcripts to identify initial codes, then collaborating to group these

codes into broader themes. To enhance the trustworthiness of the findings, member checking was carried out by sharing a summary of the themes with the interview participants for validation.

Ethical considerations

This study was approved by the Ethics Committee of Anhui Medical University (reference: 82240244). All participants were informed about the study's purpose and procedures. Written informed consent was obtained from all participants prior to their inclusion in the study.

Experimental results

This study assessed the effectiveness of VSE in teaching medical microbiology, specifically focusing on the isolation, culture, and identification of enteric pathogens. A total of 90 medical students were divided into two groups: an experimental group and a control group, with 45 students in each. Pre-tests and post-tests were administered to assess the acquisition of operational skills, the retention of theoretical knowledge, and student engagement, as detailed in the methodology section. The experimental group engaged in simulated learning through VSE before conducting hands-on experiments, while the control group received instruction using traditional teaching methods.

Operational skill acquisition

The results indicate a significant improvement in operational skill acquisition among the experimental group compared to the control group. Students in the experimental group demonstrated higher accuracy and efficiency in performing key experimental tasks, as measured by instructor evaluations using the Composition Evaluation Scale ($\alpha = 0.88$), achieving an average score of 89.6 ± 5.2 , which significantly surpassed the control group's score of 81.8 ± 6.3 ($t = 6.343$, $p < 0.01$). Notably, enhancements were particularly evident in critical steps such as the use of selective culture media, bacterial morphology observation, and biochemical reactions, where the experimental group exhibited an 18% improvement in accuracy. The controlled, interactive environment provided by VSE enabled students to engage in repetitive practice, minimizing error rates and fostering self-regulation in learning (Table 1). Furthermore, the experimental group demonstrated greater adaptability and flexibility in operational tasks, reflecting a deeper understanding of experimental procedures. For instance, they were able to independently identify and resolve issues such as simulated contamination, aligning with the educational goal of promoting autonomous learning—a critical component of self-regulated learning (SRL) theory. In contrast, students in the control group were more reliant on instructor guidance, suggesting that traditional methods may

Table 1 Evaluation of students' experimental operation skills

Evaluation Dimension	Experimental Group ($\bar{x} \pm s$)	Control Group ($\bar{x} \pm s$)	t-value	p-value
Correctness of Experimental Procedures	89.6 ± 5.2	81.8 ± 6.3	6.343	< 0.01
Fluency of Experimental Steps	87.7 ± 5.4	79.4 ± 9.5	5.121	< 0.01
Flexibility and Adaptability in Operation	87.8 ± 5.9	80.7 ± 5.8	5.782	< 0.01
Independence and Decision-making Ability	85.9 ± 5.4	76.9 ± 6.5	7.138	< 0.01

Table 2 Evaluation of students' knowledge retention

Time Point	Experimental Group ($\bar{x} \pm s$)	Control Group ($\bar{x} \pm s$)	t-value	p-value
Immediate Post-Test	87.4 ± 4.4	81.8 ± 5.0	5.669	< 0.01
Two Weeks Post-Test	85.6 ± 4.1	80.4 ± 4.8	5.551	< 0.01

limit opportunities for reflective learning and independent problem-solving.

Theoretical knowledge retention

Knowledge retention outcomes further substantiate the efficacy of VSE. Two weeks after the conclusion of the course, the experimental group achieved an average score of 85.6 ± 4.1 on the knowledge retention post-test, significantly outperforming the control group's score of 80.4 ± 4.8 ($t = 5.551$, $p < 0.01$) (Table 2).

Notably, students in the experimental group attained a 92% accuracy rate in understanding fundamental microbiological concepts, such as principles of pathogen identification and the role of culture media, compared to 80% in the control group. This indicates that the interactive learning environment facilitated by VSE, which offers immediate feedback and visual reinforcement, is particularly effective in promoting constructivist learning. In this approach, students build on prior knowledge through active engagement and contextual application.

Student motivation and engagement

VSE not only influenced skill acquisition and knowledge retention but also significantly enhanced student motivation and engagement. Likert-scale survey data indicated notable differences in experimental interest, confidence, and willingness to engage in tasks between the two groups ($p < 0.01$). Specifically, the experimental group reported that the immersive and interactive nature of VSE heightened their interest and confidence in the experimental process. This finding aligns with SDT, which highlights the importance of autonomy, competence, and relatedness in fostering intrinsic motivation. By providing a repetitive and risk-free practice environment, VSE enables students to explore, experiment, and

Table 3 Learning motivation scores (Based on likert Scale)

Evaluation Item	Experimental Group ($\bar{x} \pm s$)	Control Group ($\bar{x} \pm s$)	t-value	p-value
Interest in Experiment	4.0 ± 0.9	2.7 ± 1.0	6.503	< 0.01
Confidence in Experiment	4.3 ± 0.7	3.1 ± 0.9	7.060	< 0.01
Willingness to Participate in Experiment	4.2 ± 0.9	3.0 ± 0.8	6.150	< 0.01

Table 4 Correlation analysis between operational skills and learning motivation

Evaluation Item	r-value	p-value
Correctness of Experimental Procedures	0.33	< 0.01
Fluency of Experimental Steps	0.25	< 0.05
Flexibility and Adaptability in Operation	0.12	> 0.05
Independence and Decision-making Ability	0.27	< 0.05

refine their skills, thereby enhancing their autonomy and self-efficacy in learning (Table 3).

Qualitative feedback further revealed that VSE facilitated a clearer understanding of the logical sequence of experimental steps, particularly during complex tasks such as interpreting biochemical reactions. The real-time feedback provided by the system allowed students to reflect on their mistakes and make immediate adjustments, thus promoting reflective learning—a core element in developing deeper understanding and long-term retention.

Correlation analysis between learning behavior engagement and experimental outcomes

A Pearson correlation analysis was conducted to examine the relationship between student engagement and their performance in operational tasks. The results revealed a strong positive correlation between student engagement and skill acquisition, particularly in experimental accuracy ($r = 0.33$, $p < 0.01$), fluency of experimental steps ($r = 0.25$, $p < 0.05$), and independence and decision-making ability ($r = 0.27$, $p < 0.05$) (Table 4). Students in the experimental group who demonstrated higher engagement not only achieved better performance but also exhibited enhanced abilities to analyze and interpret results with minimal error. This correlation underscores the significance of active learning and behavioral engagement as critical factors influencing educational outcomes. Notably, those with higher engagement experienced an error rate of less than 5% in interpreting biochemical reactions, compared to 15% in the control group.

Gender-based analysis of operational skill acquisition

Gender-based differences in operational skill acquisition were observed within the experimental group (Table 5). Female students outperformed their male counterparts across multiple dimensions, including correctness of

Table 5 Comparison of experimental operation skills by gender

Gender	Correctness of Procedures ($\pm s$)	Fluency of Steps ($\bar{x} \pm s$)	Flexibility in Operation ($\bar{x} \pm s$)	Independence and Decision-making ($\bar{x} \pm s$)
Male	83.5 $\pm$ 7.6	81.0 $\pm$ 7.7	82.5 $\pm$ 6.7	80.3 $\pm$ 8.7
Female	87.5 $\pm$ 5.8	85.5 $\pm$ 9.1	85.6 $\pm$ 6.7	82.4 $\pm$ 6.2

Table 6 Comparison of operational skills by grade level in the experimental group

Grade Level	Correctness of Procedures ($\bar{x} \pm s$)	Fluency of Steps ($\bar{x} \pm s$)	Flexibility in Operation ($\bar{x} \pm s$)	Independence and Decision-making ($\bar{x} \pm s$)
Freshman	84.9 $\pm$ 7.6	83.1 $\pm$ 9.6	83.4 $\pm$ 6.7	79.7 $\pm$ 8.0
Sophomore	86.6 $\pm$ 6.1	83.9 $\pm$ 7.7	85.2 $\pm$ 6.9	83.3 $\pm$ 6.3

procedures (87.5 $\pm$ 5.8 vs. 83.5 $\pm$ 7.6), fluency (85.5 $\pm$ 9.1 vs. 81.0 $\pm$ 7.7), and flexibility (85.5 $\pm$ 9.1 vs. 81.0 $\pm$ 7.7). This observation indicates a potential interaction between gender and learning within the VSE environment. However, these findings should be interpreted with caution. Without a comparative analysis of gender-based performance in the control group, it is not possible to conclude that VSE itself is the primary cause of this difference or that it particularly benefits female students over traditional methods. This result highlights an area for future investigation, where a more targeted research design could explore the underlying reasons for this performance gap.

Impact of grade level on experimental skills

Differences in operational skill acquisition were also observed across grade levels (Table 6). Sophomores consistently outperformed freshmen in correctness (86.6 $\pm$ 6.1 vs. 83.1 $\pm$ 9.6) and fluency (83.9 $\pm$ 7.7 vs. 83.1 $\pm$ 9.6), reflecting the expected progression of learning. These findings align with scaffolding theory, where more experienced learners are better able to integrate complex tasks. This pattern serves as a form of construct validity for our skill assessment, confirming that it is sensitive to different levels of prior student experience. However, flexibility showed a smaller improvement, suggesting that certain higher-order skills may require further support, such as targeted interventions or guided discovery learning.

Effect of study habits on experimental operation skills

Study habits were found to significantly influence students' experimental operation skills (Table 7). Students with higher study habit scores ([4, 5]) outperformed their peers in all measured dimensions: accuracy (89.1 $\pm$ 4.9 vs. 82.3 $\pm$ 7.1), fluency (88.0 $\pm$ 5.7 vs. 79.1 $\pm$ 9.0), flexibility (87.6 $\pm$ 5.2 vs. 80.9 $\pm$ 6.6), and independence in decision-making (84.4 $\pm$ 6.2 vs. 78.4 $\pm$ 7.4). Specifically,

Table 7 Impact of study habits on experimental operation skills

Study Habit Score	Accuracy of Operation ($\bar{x} \pm s$)	Fluency of Operation ($\bar{x} \pm s$)	Flexibility in Operation ($\bar{x} \pm s$)	Independence and Decision-making ($\bar{x} \pm s$)
High Study Habit Score (4–5)	89.1 $\pm$ 4.9	88.0 $\pm$ 5.7	87.6 $\pm$ 5.2	84.4 $\pm$ 6.2
Low Study Habit Score (1–3)	82.3 $\pm$ 7.1	79.1 $\pm$ 9.0	80.9 $\pm$ 6.6	78.4 $\pm$ 7.4

Table 8 User satisfaction analysis of VSE system

Evaluation Item	Experimental Group ($\bar{x} \pm s$)	Satisfaction Percentage (%)
Ease of Use of Experimental System	4.5 $\pm$ 0.6	95.6
Clarity of Experimental Steps	4.5 $\pm$ 0.9	86.7
Timeliness of Feedback Provided	4.6 $\pm$ 0.5	97.8
Willingness to Continue Using VSE	4.8 $\pm$ 0.6	93.3

the high study habit group showed significantly superior performance in both accuracy and fluency, suggesting that effective study habits are particularly beneficial for enhancing procedural precision and task execution efficiency. Although students with high study habit scores also demonstrated better flexibility, the difference in this dimension was less pronounced, indicating that while study habits contribute to adaptability, their influence on flexibility may be more limited. This suggests that factors such as prior experience, cognitive strategies, and inherent problem-solving abilities could also play a substantial role in shaping students' adaptability in experimental tasks. These findings underscore the importance of developing meta-cognitive strategies that not only foster self-awareness and independent decision-making but also enhance flexibility and problem-solving skills—key elements for mastering complex experimental procedures.

User satisfaction with the VSE system

The high levels of satisfaction reported by students regarding the VSE system underscore its effectiveness in enhancing learning outcomes (Table 8). Participants rated the ease of use at 4.5 $\pm$ 0.6 (95.6%), and clarity of experimental steps at 4.5 $\pm$ 0.9 (86.7%), along with timeliness of feedback at 4.6 $\pm$ 0.5 (97.8%). Notably, 93.3% expressed a willingness to continue using VSE, highlighting its potential as a sustainable and scalable tool for medical education. This positive reception reflects the alignment of VSE with constructivist principles, emphasizing active engagement and student-centered learning.

Comparison of student feedback

Feedback from students in both groups highlights the significant impact of VSE on learning outcomes (Table 9). A substantial 97.7% of the experimental group reported

Table 9 Feedback on learning experience from experimental and control groups

Student Feedback Question	Support Rate from Experimental Group (%)	Support Rate from Control Group (%)
VSE System Enhanced Experimental Operation Skills	97.7	82.1
Interactivity and Feedback During Experiment Enhanced Learning Interest	93.1	79.9
Willingness to Continue Using VSE for Learning	95.4	71.1

that VSE enhanced their operational skills, in contrast to only 82.1% in the control group. Furthermore, an impressive 95.4% of students in the experimental group expressed a willingness to continue using VSE, demonstrating the motivational benefits of interactive learning environments in fostering sustained interest and engagement.

Discussion and conclusions

This study investigated the impact of VSE on student learning outcomes and behavioral intentions in medical education, focusing specifically on operational skill acquisition, knowledge retention, and engagement. By employing an integrated theoretical framework of Self-Determination Theory (SDT) and the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2), our findings provide a multi-faceted explanation for VSE's effectiveness, revealing a synergistic interplay between intrinsic motivational factors and external technological conditions.

Enhancement of learning motivation and engagement through SDT

The immersive and interactive nature of VSE significantly enhanced students' motivation and engagement, a finding that can be interpreted through the lens of SDT. Our results show that the VSE learning environment, which allows for repetitive, risk-free practice and provides immediate feedback, directly supports two of the three basic psychological needs central to SDT. The ability for students to master procedures at their own pace enhanced their sense of competence, while the freedom to make and correct mistakes without direct instructor intervention fostered a sense of autonomy over their learning process. This aligns with previous research suggesting that autonomy-supportive learning environments significantly promote intrinsic motivation [18]. The experimental group's mean operational skills score (89.6 ± 5.2) significantly surpassed the control group's (81.8 ± 6.3), which we posit is not merely a result of more practice, but a consequence of motivationally enhanced

learning fueled by the satisfaction of these psychological needs. This finding is consistent with meta-analyses by Merchant et al. [23] which confirm the powerful impact of immersive environments on learning outcomes.

Technology acceptance and learning outcomes through UTAUT2

Beyond intrinsic motivation, the successful implementation of VSE is contingent upon students' acceptance of the technology itself, a domain explained by UTAUT2. The study's findings underscore the importance of several key UTAUT2 constructs. The significant improvement in learning outcomes directly reflects Performance Expectancy; students who perceived the VSE as an effective tool for achieving higher grades and better skills were more likely to engage with it. The high user satisfaction ratings regarding the system's ease of use (95.6%) highlight the critical role of Effort Expectancy. An intuitive, well-designed VSE lowers the cognitive barrier to entry, allowing students to focus on the learning content rather than struggling with the technology [24]. This finding corroborates research by Kim & Kim [25] on the importance of usability in medical education technology. Furthermore, qualitative feedback revealed that students were motivated by the novelty and peer recognition of using an innovative tool, pointing to the influence of Social Influence. Finally, the provision of a fully functional system and technical support acted as crucial Facilitating Conditions, ensuring a smooth learning experience. Our study thus empirically demonstrates that for VSE to be effective, it must be perceived by students as a tool that is both valuable for performance and easy to use.

Skill mastery, engagement, and the interplay of theories

The strength of our integrated framework lies in its ability to explain how these internal and external factors interact. The VSE's ability to provide immediate feedback (a design feature) enhances a student's sense of competence (SDT), which in turn reinforces their belief that the system is helping their academic performance (Performance Expectancy, UTAUT2). This positive feedback loop fosters deeper engagement, which, as our correlation analysis shows ($r = 0.33$ for accuracy), is strongly linked to better skill acquisition. This finding is consistent with Kleinert et al. [26], who concluded that virtual simulations enhance operational skills. However, our study extends this by proposing a clear mechanism: technology acceptance (UTAUT2) serves as a gateway to the pedagogical environment, where the satisfaction of psychological needs (SDT) can occur, leading to enhanced engagement and skill mastery.

Challenges in developing independence and future directions

Despite VSE's advantages in enhancing skill mastery, the study revealed limited improvements in students' independence and decision-making abilities. According to SDT, fostering autonomy requires not only opportunities for practice but also the freedom to make decisions and explore alternative solutions. While the structured nature of VSE effectively supports skill acquisition, it may inadvertently limit students' capacity to exercise independent judgment, as they tend to rely on the system's feedback rather than their own problem-solving strategies.

This finding highlights a critical design challenge for the next generation of VSE. To bridge this gap, future development should focus on adapting VSE to promote greater autonomy. Looking ahead, the integration of Artificial Intelligence (AI) and more advanced Virtual Reality (VR) technologies offers a promising path forward [27, 28].

AI-assisted learning can transform VSE from a static, guided platform into an adaptive, personalized learning partner. For instance, an AI engine could offer personalized feedback that is less directive and more Socratic, prompting students with questions rather than providing immediate answers [29]. It could also create dynamic, open-ended scenarios that adapt in real-time to student decisions, presenting alternative pathways and consequences, thereby promoting genuine decision-making [30]. Furthermore, advanced VR can simulate more complex and ambiguous clinical scenarios, enhancing students' problem-solving skills in a risk-free yet realistic environment [31]. Future research should therefore explore how these technologies can be integrated into VSE systems to specifically target autonomy and competence development, ultimately fostering more independent and confident medical professionals.

Limitations of the study

Despite the robust findings, this study has several limitations that should be acknowledged, providing context for the interpretation of the results.

Firstly, the study's sample was drawn from a single medical university in China. This limited scope restricts the generalizability of our findings. Cultural contexts, specific curricula, and students' prior exposure to digital learning technologies can vary significantly across institutions and countries, potentially influencing both technology acceptance and learning outcomes.

Secondly, our research relied on newly developed questionnaires for assessing factors like student engagement and study habits. While we have ensured transparency by detailing their development process and reporting their internal consistency reliability (Cronbach's α), these instruments have not undergone the

extensive, longitudinal validation process typical of standardized, published scales.

Thirdly, the assessment of operational skills, while conducted with high inter-rater reliability using a detailed rubric, remains a proxy measure for real-world laboratory performance. The simulated environment, by its nature, cannot fully replicate the tactile feedback and unpredictable variables of a physical laboratory.

Fourthly, the qualitative data collection relied on detailed note-taking rather than audio recordings. While this approach was intentionally chosen to enhance participant comfort and encourage candid responses, we acknowledge it as a methodological limitation. The absence of verbatim transcripts introduces the potential for researcher bias in data capture and precludes the possibility of inter-coder reliability checks, a key component for ensuring analytical rigor. Consequently, while our thematic analysis provides valuable insights, its depth and verifiability are somewhat constrained. Future research in this area should aim to incorporate audio recording and transcription to support a more robust and transparent qualitative analysis.

Finally, the characterization of the control group was limited to "traditional laboratory methods." A more detailed analysis of the pedagogical practices within the control condition could have provided a more nuanced comparison and helped to isolate the specific effects of the VSE intervention with greater precision.

Future research directions

The limitations of the present study directly inform several promising avenues for future research that can build upon our findings. First, to address the issue of generalizability, future research should aim to conduct cross-cultural and multi-institutional studies. Replicating this study with larger, more diverse student populations would be crucial to validate the broader applicability of our findings and the utility of the integrated SDT-UTAUT2 framework. Second, there is a clear need for the development and validation of standardized instruments for evaluating learning experiences and outcomes within VSE environments. Such tools would greatly enhance the comparability and methodological rigor of future research in this rapidly growing field. Third, while our study measured knowledge retention over two weeks, longitudinal studies are essential to assess the long-term impact of VSE. Tracking students over several months or even into their clinical practice is critical to determine the durability of VSE-acquired skills and, most importantly, their successful transfer to real-world professional contexts. Finally, building on our finding regarding the challenge in developing independence, future work should employ experimental designs to compare different VSE features. For example, researchers could directly compare

a highly structured, guided VSE with a more open-ended, “sandbox” version to test their differential impacts on foundational skill acquisition versus higher-order abilities like independent problem-solving and critical thinking.

Conclusions and implications for practice

This study provides robust evidence for the effectiveness of VSE in medical microbiology education. By integrating Self-Determination Theory (SDT) and the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2), our research demonstrates that the success of VSE is driven by a powerful synergy between intrinsic motivational factors, rooted in psychological needs, and external conditions related to technology acceptance.

The findings underscore the importance of designing VSE systems that not only ensure technical fidelity but also intentionally promote student autonomy and engagement. For educators and instructional designers, the practical implications are clear:

1. Design for Motivation, Not Just Content: VSE development must move beyond replicating physical experiments and explicitly incorporate features that foster student autonomy (e.g., flexible pathways, self-pacing) and competence (e.g., immediate, constructive, and non-judgmental feedback), in line with SDT principles.
2. Prioritize Usability and User Experience: To ensure technology acceptance (UTAUT2), VSE systems must be intuitive, reliable, and easy to navigate. A steep learning curve for the tool itself can create a significant barrier, detracting from the primary learning objectives and undermining both student effort and performance expectations.
3. Provide Holistic Support: The successful implementation of VSE is not just about providing software. It requires building a supportive ecosystem with strong facilitating conditions, including robust technical support for students and comprehensive training for educators to help them effectively integrate these powerful tools into their pedagogy.

In conclusion, when designed and implemented thoughtfully, VSE stands as a powerful, scalable and engaging tool with the potential to transform medical laboratory education, offering an effective alternative to traditional methods.

Abbreviations

VSE	Virtual Simulation Experiments
SDT	Self-Determination Theory
UTAUT2	Unified Theory of Acceptance and Use of Technology 2
VR	Virtual Reality
UNESCO	United Nations Educational, Scientific, and Cultural Organization
MOOCs	Massive Open Online Courses
SRL	Self-regulated learning

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT for the purpose of Chinese translation and language polishing. After utilizing this tool/service, the author(s) reviewed and edited the content as necessary and take(s) full responsibility for the content of the publication.

Authors' contributions

The contributions of the authors are as follows: Kaiyue Li : Contributed to the conceptualization and design of the study, as well as the drafting of the initial manuscript. Responsible for the acquisition of data and initial analysis. Qun Li : Played a significant role in the interpretation of data and provided critical feedback on the manuscript. Assisted in the design of the study and contributed to the final editing. Linding Wang: Involved in the collection and assembly of data, as well as the drafting of specific sections of the manuscript. Participated in the interpretation of results. Xiaonan Wang: Responsible for the statistical analysis of the data and the preparation of figures and tables. Contributed to the drafting and revision of the manuscript. Xiaojuan Ding : Contributed to the acquisition of data and the drafting of the manuscript. Assisted in the preparation of figures and tables. Boyu Liu: Oversaw the overall direction and planning of the study. Acted as the guarantor for the manuscript, ensuring the integrity of the work as a whole, from inception to published article. Responsible for the critical revision of the manuscript for important intellectual content and final approval of the version to be published. All authors have read and approved the final manuscript. Corresponding Author: Boyu Liu, School of Basic Medical Sciences, Anhui Medical University, Hefei, China. E-mail: liuboyu@ahmu.edu.cn.

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Data availability

The data generated and analyzed in this study are available as Related files at the end of the article and will be made publicly accessible upon publication. Readers can directly access these materials by referring to the relevant section at the conclusion of the paper.

Declarations

Ethics approval and consent to participate

The study was approved by the Ethics Committee of Anhui Medical University (reference: 82240244). All participants were informed about the study's purpose and procedures. The participants were informed that their participation was voluntary, that they had the right to withdraw from the study at any time, and that their personal information would be protected and kept confidential. Written informed consent was obtained from all participants prior to their inclusion in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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