



DESIGN AND EFFECTIVENESS OF A VR–AI INTEGRATED BUSINESS MATHEMATICS E-MODULE FOR ENHANCING CRITICAL AND CREATIVE THINKING IN HIGHER EDUCATION

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ABSTRACT

Aim/Purpose	This study aims to develop and empirically evaluate a VR–AI integrated Business Mathematics e-module designed to enhance undergraduate students' critical and creative thinking in higher education.
Background	Business mathematics instruction in higher education frequently lacks structured, immersive resources that integrate Virtual Reality (VR) and Artificial Intelligence (AI) to promote deep analytical and creative competencies. Initial observations at Institut Bisnis dan Teknologi Indonesia confirmed that instruction remained predominantly teacher-centered, with limited opportunities for contextual problem-solving. Unlike prior VR or AI studies that deploy these technologies as supplementary tools, this study embeds them as core components of a structured PBL-based e-module – a distinguishing design feature validated across three empirical trial phases.

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Methodology	A design-based research approach was adopted using the PLOMP development model, comprising preliminary investigation, prototype development, and assessment phases. Instruments included expert validation sheets (LORI), the USE Questionnaire, observation sheets, interview guides, and essay-type tests targeting critical and creative thinking. Content validity was established using the Content Validity Ratio (CVR = 1.00) across all instruments. Reliability of the critical thinking test was confirmed by Cronbach's $\alpha = 0.883$, and the creative thinking test by $\alpha = 0.817$, both indicating high reliability. Participants included 70 undergraduate Digital Business students across a pilot test (n = 9), First Field Trial (n = 33), and Second Field Trial (n = 28).
Contribution	This paper contributes an empirically validated VR–AI integrated e-module framework that combines 360° immersive simulation with AI-facilitated adaptive interaction within a structured Problem-Based Learning (PBL) approach, specifically targeting the development of critical and creative thinking in business mathematics.
Findings	The e-module achieved high validity (design: M = 4.40, SD = 0.29; media: M = 4.42, SD = 0.32; content: M = 4.57, SD = 0.05; all categorized as Highly Valid). Practical usability improved from 72.17% (First Field Trial) to 86.39% (Second Field Trial). Students' critical thinking scores rose from M = 88.38 (SD = 5.12, 95% CI [86.56, 90.20]) to M = 93.42 (SD = 4.18, 95% CI [91.80, 95.04]), and creative thinking scores from M = 88.28 (SD = 5.34, 95% CI [86.39, 90.17]) to M = 92.86 (SD = 4.05, 95% CI [91.29, 94.43]), between the two field trials, both substantially exceeding the minimum mastery criterion of 80.
Recommendations for Practitioners	Higher education practitioners are encouraged to integrate VR and AI technologies into structured, PBL-based learning modules to create interactive, contextual, and student-centered environments that develop critical and creative thinking competencies.
Recommendations for Researchers	Future researchers should expand participant diversity across study programs and institutions, explore broader subject areas, and develop more rigorous comparative and longitudinal designs to strengthen generalizability.
Impact on Society	The study supports the cultivation of graduates equipped with critical and creative thinking competencies essential for navigating complex, real-world challenges in the digital and global economy.
Future Research	Future studies should examine VR-AI integration across diverse educational contexts, address VR accessibility and technical barriers, and develop more varied assessment instruments aligned with HOTS frameworks.
Keywords	virtual reality, artificial intelligence, business mathematics, e-module, critical thinking, creative thinking, higher education, immersive learning, problem-based learning, design-based research, PLOMP model

INTRODUCTION

Higher-order thinking abilities, particularly critical and creative thinking, have become indispensable competencies for graduates navigating the complexities of the twenty-first century. Rapid technological change, socioeconomic transformation, and the accelerating expansion of knowledge demand individuals capable of analyzing problems critically and generating innovative solutions (Agustini et al., 2022; Santyasa et al., 2021; Warpala et al., 2025). Without these skills, graduates face increasing difficulty adapting to shifting professional and societal demands.

Higher education institutions bear a strategic responsibility for cultivating these competencies. Improving the quality of university-level learning has therefore emerged as a central concern among educational researchers and practitioners (Chaname-Chira et al., 2024; Veluvali & Suriseti, 2022). Advances in digital technology have opened new possibilities for instructional innovation, encompassing e-modules, interactive multimedia, Augmented Reality (AR), and Virtual Reality (VR) (Adriyanto et al., 2021; Darmawan et al., 2024; Hartawan et al., 2024; Makransky & Petersen, 2021). Yet, technological integration alone does not guarantee meaningful learning. Learning environments must be deliberately designed to support deep cognitive engagement (Roy & Janardhanan, 2025).

A key theoretical foundation for this design is constructivism, which holds that learners construct knowledge through active engagement with meaningful contexts rather than through passive reception of information (Makransky & Petersen, 2021). Cognitive Load Theory further informs instructional design by emphasizing the importance of presenting complex information in ways that optimize working memory and support schema formation (Izouaouen et al., 2025). Experiential learning theory additionally supports the use of simulated environments that allow learners to connect abstract concepts to authentic situations (Kolb, 1984). Within this framework, VR environments offer particular promise: they allow learners to experience realistic business simulations in immersive 360° settings, bridging the gap between theoretical knowledge and real-world application (Azher et al., 2023; Ravichandran & Mahapatra, 2023; Ummihusna & Zairul, 2022).

Despite growing interest in VR-based learning, a clear gap persists in the literature. Most existing VR applications function as supplementary tools rather than being systematically embedded within structured instructional materials (Shuen et al., 2024). Empirical studies that integrate VR directly into learning modules with an explicit focus on enhancing critical and creative thinking in higher education mathematics remain limited. Furthermore, the role of Artificial Intelligence (AI) in such environments has received insufficient attention. Intelligent tutoring systems and AI-facilitated adaptive feedback represent a distinct yet underexplored dimension of immersive learning design, with demonstrated potential to support analytical reasoning and personalized guidance (Rong et al., 2022; Sing et al., 2025). This gap is especially evident in business mathematics, where abstract concepts frequently challenge students' ability to connect theory with real-world economic and commercial contexts (Adolat, 2024; Suharta & Astawa, 2024).

Contextual observations at Institut Bisnis dan Teknologi Indonesia revealed that business mathematics instruction in the Digital Business Study Program remained predominantly teacher-centered. A preliminary diagnostic assessment administered to students in the preceding academic year indicated that fewer than 48% achieved the minimum mastery criterion (score ≥ 80) on problem-solving tasks requiring analytical and creative reasoning, and the cohort mean on higher-order thinking tasks was 67.4, substantially below the program standard of 80. Students had limited exposure to contextual problem-solving environments, and available instructional materials did not systematically scaffold the development of critical or creative thinking competencies. These institutional conditions provided direct empirical motivation for developing an alternative learning approach that integrates immersive simulation with structured pedagogical scaffolding.

To address these challenges, this study integrates VR and AI within a structured Business Mathematics learning environment using the PLOMP development framework, which encompasses preliminary investigation, prototype design, and assessment phases (Suharta & Sudiarta, 2022). Within the developed e-module, VR-based simulations immerse learners in authentic business scenarios, while AI serves as an adaptive facilitator, providing prompts, feedback, and guided questioning that support analytical reasoning and creative ideation during mathematical problem-solving. The study is guided by three research questions: (1) How valid is the VR-AI-integrated Business Mathematics e-module developed using the PLOMP model? (2) How practical is the developed e-module when applied in higher education learning environments? (3) How effective is the e-module in enhancing students' critical and creative thinking abilities in Business Mathematics?

The following sections present a review of the relevant literature, a description of the research methodology, the results of validation and field trials, a discussion of findings in relation to theoretical frameworks, and a conclusion that identifies the study's contributions, limitations, and directions for future research.

LITERATURE REVIEW

HIGHER-ORDER THINKING IN HIGHER EDUCATION

Critical and creative thinking represent two interrelated dimensions of higher-order thinking skills (HOTS) that are essential for success in complex, knowledge-intensive environments. Critical thinking involves the capacity to analyze, evaluate, and synthesize information systematically, while creative thinking encompasses the ability to generate novel ideas, explore multiple solutions, and connect concepts in original ways (Agustini et al., 2022; Tegeh, Santyasa, et al., 2022). Both competencies are closely aligned with the intellectual demands of the twenty-first century and with Problem-Based Learning (PBL), an instructional approach in which students engage with ill-structured, authentic problems that require iterative analysis and creative resolution (Asri et al., 2024; Santyasa et al., 2021).

Despite their recognized importance, studies consistently show that traditional lecture-based mathematics instruction rarely cultivates these higher-order skills. Abstract mathematical content, disconnected from real-world contexts, tends to promote surface-level understanding and procedural compliance rather than deep conceptual engagement (Hartawan et al., 2024; Suharta & Astawa, 2024). The literature, therefore, calls for instructional innovations that provide learners with authentic, contextualized problem environments, which is precisely the gap this study addresses.

VIRTUAL REALITY IN EDUCATION

Virtual Reality (VR) refers to computer-generated environments that simulate real or imagined settings and allow users to interact with them in an immersive manner. In educational contexts, VR has been applied across disciplines including science, engineering, health, and the social sciences, with consistent evidence of positive effects on student engagement, motivation, and conceptual understanding (Cho & Park, 2023; Han, 2023; Ravichandran & Mahapatra, 2023; Rong et al., 2022; Sathish Kumar et al., 2024). VR's educational value is explained theoretically by the Cognitive Affective Model of Immersive Learning (CAMIL), which posits that immersive environments enhance learning by simultaneously engaging cognitive and affective processes, thereby facilitating deeper information processing and more durable knowledge construction (Makransky & Petersen, 2021).

In business and economics education, VR environments that simulate commercial settings, such as retail stores, supply chains, and financial decision-making scenarios, allow learners to observe and interact with phenomena that would be inaccessible in conventional classrooms. Bachiller et al. (2023) demonstrated that VR can effectively represent real-world professional environments, while Ummi-husna and Zairul (2022) documented VR's capacity to deepen situational understanding in architecture education – findings that generalize to any discipline requiring the application of abstract knowledge to concrete contexts. Despite these advances, most VR implementations remain supplementary rather than being pedagogically integrated into structured learning materials. Notably, several studies have reported more limited effects of VR on learning outcomes when it is used without embedded instructional scaffolding. Makransky and Lilleholt (2018) found that purely immersive VR environments without guided pedagogical support could increase cognitive load without improving learning performance, underscoring the necessity of the structured PBL framework adopted in the present study.

AI IN LEARNING ENVIRONMENTS

Artificial Intelligence (AI) encompasses a range of technologies – including intelligent tutoring systems, adaptive learning platforms, generative AI, and learning analytics – that have demonstrated significant potential to personalize and enhance educational experiences (Sing et al., 2025; Suharta et al., 2025). In learning contexts, AI can serve as an adaptive facilitator, identifying student misconceptions, providing targeted feedback, adjusting task difficulty based on individual performance, and prompting deeper analytical thinking through guided questioning. These functions align with self-regulated learning theory, which emphasizes the importance of metacognitive monitoring and adaptive strategy use in effective learning (Rong et al., 2022).

Recent empirical evidence confirms the value of AI integration in mathematics education specifically. Suharta et al. (2025) demonstrated that an AI-assisted digital module for realistic mathematical problem modeling significantly improved students' mathematical literacy. Sudarma et al. (2025) further demonstrated that AI-powered diagnostic systems can analyze individual learner intelligence profiles and automatically deliver differentiated digital content to optimize learning outcomes – evidence of AI's capacity to function as an adaptive instructional partner responsive to individual cognitive characteristics. Rong et al. (2022) found that the combination of AI and VR had positive effects on student concentration and creativity. These findings highlight the importance of treating AI not merely as a content-delivery tool but as an interactive pedagogical partner capable of scaffolding analytical and creative thinking processes. However, not all AI implementations have yielded uniformly positive results. Huang et al. (2023) caution that AI-driven feedback systems may be less effective when students lack metacognitive awareness, suggesting that the pedagogical design surrounding AI features, rather than the AI alone, determines its educational impact. This nuance reinforces the rationale for embedding AI facilitation within a structured PBL sequence in the present study.

MATHEMATICS LEARNING CHALLENGES AND E-MODULES

Business mathematics presents distinctive pedagogical challenges. Its content (encompassing functions, sequences, and series, demand-supply analysis, and surplus calculations) involves abstract relationships that students frequently struggle to connect to authentic commercial contexts (Adolat, 2024). E-modules represent one promising response to these challenges, offering structured, flexible, and digitally accessible learning experiences that can be enriched with multimedia and interactive elements (Hartawan et al., 2024; Putri et al., 2023; Sudarma & Sukmana, 2021; Tegeh, Santyasa, et al., 2022). Sudarma and Sukmana (2021) demonstrated that digital content designed in accordance with information processing theory can meaningfully improve students' cognitive performance, providing empirical support for the cognitive benefits of well-structured e-module design. Tegeh, Jampel, et al. (2022) further showed that PBL-based e-modules developed at the elementary level enhanced student engagement and problem-solving abilities, reinforcing the cross-context pedagogical appropriateness of structuring e-modules around PBL principles. Suratnu (2023) demonstrated the effectiveness of module-based instruction developed using systematic design models, while Chrishanty et al. (2025) showed that deep learning-integrated e-learning tools can enhance pedagogical competence. These precedents collectively support the rationale for developing a VR–AI integrated e-module specifically designed to address the contextual and cognitive demands of business mathematics.

RESEARCH GAP AND CONCEPTUAL FRAMEWORK

Taken together, the literature reveals a clear and substantive gap: while VR and AI have each demonstrated independent educational value, their systematic integration within a structured, pedagogically grounded e-module focused on critical and creative thinking in business mathematics remains largely unexplored. Existing studies typically either apply VR without AI-facilitated interaction, employ AI without immersive simulation, or implement these technologies as supplementary tools rather than as core components of a comprehensive instructional design. Moreover, few studies have applied systematic design research frameworks, such as the PLOMP model, to generate empirical evidence concerning the validity, practicality, and effectiveness of such integrated learning environments.

The present study addresses this gap by developing and empirically evaluating a VR-AI integrated Business Mathematics e-module grounded in PBL pedagogy and constructivist learning theory. The conceptual framework posits that immersive VR simulations of authentic business scenarios, combined with AI-facilitated adaptive prompting within a structured PBL sequence, will create the cognitive and affective conditions necessary for the development of higher-order thinking skills.

METHODS

RESEARCH DESIGN

This study employed a design-based research (DBR) methodology, characterized by iterative cycles of design, development, testing, and refinement aimed at producing both a functional learning product and theoretical insights into effective design principles (Suharta & Sudiarta, 2022). The selected development model was the PLOMP Model, comprising three phases: Preliminary Research, Development (Prototyping), and Assessment. The PLOMP model was selected over alternative frameworks such as ADDIE or Borg and Gall because it explicitly incorporates formative evaluation within each development cycle and is specifically designed for multi-phase educational research that generates both product and process knowledge. The modified PLOMP model applied in this study is illustrated in Figure 1.

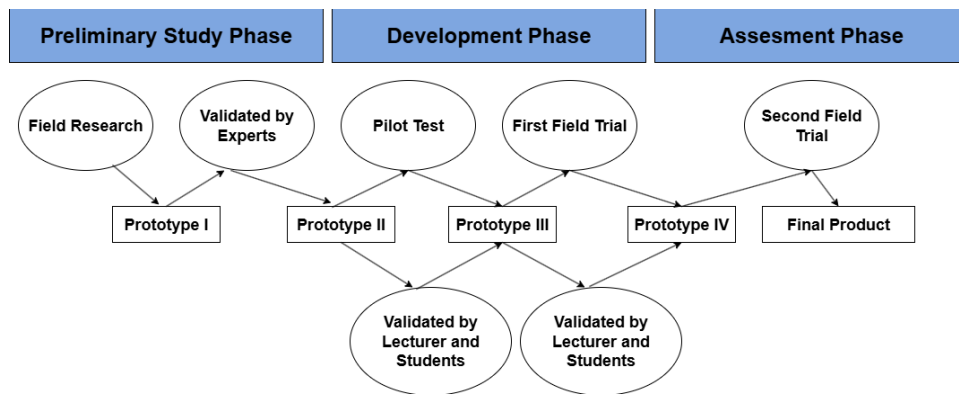


Figure 1. Modified PLOMP development model

PARTICIPANTS

Participants were undergraduate students enrolled in the Digital Business Study Program at Institut Bisnis dan Teknologi Indonesia, Indonesia, during the 2024-2025 academic year. All participants were second-semester students studying Business Mathematics as a required course. Participants ranged in age from 18 to 21 years, and the groups included both male and female students with a gender composition typical of the Digital Business program. None of the participants had prior formal experience with VR-based learning tools, although all were familiar with standard digital devices (smartphones, laptops, and tablets). Purposive sampling was employed to ensure participants represented the target population for whom the e-module was designed.

Three participant groups were involved across the development phases. The pilot test (*Uji Coba Terbatas*) comprised nine students selected to represent diverse academic achievement levels (three each from low, medium, and high achievement categories), enabling a broad assessment of initial usability. The First Field Trial (*Uji Coba Lapangan 1*) involved 33 students from a different class, and the Second Field Trial (*Uji Coba Lapangan 2*) involved 28 students from a further distinct class. Separation across classes ensured that trial groups had not been exposed to earlier prototype versions. Ethical approval for this study was obtained from the institutional research ethics committee of Institut

Bisnis dan Teknologi Indonesia, and informed consent was secured from all participants prior to data collection.

INSTRUMENTS

Four categories of instruments were used in this study, all of which were validated by five expert judges using the Content Validity Ratio (CVR) formula. All instruments achieved a CVR value of 1.00 and a Content Validity Index (CVI) of 1.00, confirming high content validity across all items. The five expert validators were Dr. Kadek Suartama (instructional technology), Dr. Sukra (mathematics education), Prof. Agustini (educational technology), Prof. Parwati (mathematics education), and Prof. Tegeh (educational technology).

Expert validation instruments employed the Learning Object Review Instrument (LORI), which covered three aspects: content (21 items, CVI = 1.00), learning design (14 items, CVI = 1.00), and media (16 items, CVI = 1.00). Items were rated on a five-point Likert scale assessing relevance, accuracy, pedagogical quality, and technical adequacy. The validity threshold was set at $\bar{x} > 3.40$ (Valid) and $\bar{x} > 4.20$ (Highly Valid), following Laksana (2024), who established these criteria based on convergent validity evidence from a systematic review of learning media validation studies in Indonesian higher education.

Practicality instruments comprised: (a) an observation sheet (19 items, CVI = 1.00) structured across six activity phases (Preliminary Activities (items 1–5), Problem Orientation (items 6–7), Group Investigation (items 8–9), Solution Development and Presentation (items 10–11), Analysis and Evaluation (items 12–15), and Closing Activities (items 16–19)) rated on a five-point scale from Very Poor (SK) to Very Good (SB), with classification thresholds of Good ($0.60 < \bar{x} \leq 0.80$) and Very Good ($\bar{x} > 0.80$); (b) a USE Questionnaire (21 items, CVI = 1.00) assessing four dimensions (Usefulness (7 items, 1–7), Ease of Use (4 items, 8–11), Ease of Learning (5 items, 12–16), and Satisfaction (5 items, 17–21)) on a five-point Likert scale from Strongly Disagree to Strongly Agree, with scores of 61%–80% classified as Practical and above 80% as Highly Practical; and (c) structured interview guides for students (20 items, CVI = 1.00) and lecturers (18 items, CVI = 1.00) to capture qualitative perceptions of usability, VR experience, and learning engagement. Interview data were analyzed using a thematic analysis procedure comprising five steps: (1) transcription of audio-recorded interviews; (2) initial open coding of meaningful units; (3) grouping of codes into emerging themes; (4) member-checking with three representative participants to verify theme accuracy; and (5) selection of representative quotations to illustrate each theme in the results.

Effectiveness instruments consisted of two essay-type tests: (a) a Critical Thinking Skills Test comprising eight essay items (two items per indicator) assessing four indicators aligned with SOLO taxonomy levels: Interpretation (Multistructural – set theory problems), Analysis (Relational – linear functions in business), Evaluation (Relational – arithmetic and geometric sequences), and Inference (Extended Abstract – consumer and producer surplus); and (b) a Creative Thinking Skills Test comprising eight essay items assessing four indicators: Fluency (Multistructural), Flexibility (Relational), Originality (Extended Abstract), and Elaboration (Extended Abstract), with content parallel to the critical thinking test. Scoring for both tests used a five-level rubric (0–4): 0 = no response; 1 = irrelevant answer; 2 = relevant but incorrect; 3 = partially correct; 4 = fully correct and complete. Both tests were validated by the same five expert judges (CVI = 1.00) and piloted with 30 students. Statistical validity (Pearson correlation with $r\text{-table} = 0.361$, $df = 28$, $\alpha = 0.05$) confirmed that all items were valid ($r\text{-values}$: 0.570–0.843 for critical thinking; 0.472–0.824 for creative thinking). Reliability analysis yielded Cronbach's $\alpha = 0.883$ for the critical thinking test and $\alpha = 0.817$ for the creative thinking test, both indicating high internal consistency.

PROCEDURE

The research procedure followed the three PLOMP phases. In the Preliminary Research Phase, a needs analysis was conducted through classroom observations, student questionnaires, interviews

with lecturers, and curriculum review. This phase identified that learning materials did not support the development of critical and creative competencies, that instruction was predominantly teacher-centered, and that students lacked access to contextualized problem-solving resources. Based on curriculum analysis, eight core topics were identified for integration into the e-module: Introduction to Business Mathematics and Set Theory; Relations and Functions; Linear Functions and Linear Equations; Applications of Linear Functions in Demand and Supply; Applications of Linear Functions in Revenue and Cost; Arithmetic Sequences and Series; Geometric Sequences and Series and Compound Interest; and Consumer and Producer Surplus.

In the Development Phase, the initial prototype (Prototype I) was designed following PBL syntax. Each of the eight learning units opened with a problem orientation delivered through a 360° VR simulation depicting an authentic business scenario. Activities progressed through individual or group investigation, collaborative discussion and analysis, solution presentation, and structured reflection. Each unit was designed to span one to two 90-minute class sessions, depending on the topic's complexity. AI-powered virtual characters within the VR environment served as interactive facilitators, explaining mathematical and business concepts, presenting realistic data (graphs, sales reports, financial cases), and prompting students' analytical reasoning through adaptive questioning. The AI component provided context-specific prompts aligned with each unit's problem scenario, guiding students to identify relevant variables, evaluate assumptions, and generate alternative solutions without directly providing answers. The visual and textual layout of all module components was developed in accordance with message design principles for analytical visual texts and images (Sudarma et al., 2015), ensuring that the arrangement of text, diagrams, and interactive screen elements was structured to optimize readability, visual coherence, and cognitive load management. The lecturer's role throughout implementation was facilitative rather than instructional: monitoring student engagement, supporting group dynamics, addressing technical VR difficulties, and prompting reflection at key learning junctures. Each unit also contained material explanations, interactive assignments, formative tests, assessment rubrics, and references. Prototype I was submitted for expert validation, and feedback was incorporated to produce Prototype II.

Prototype II was tested in the pilot study with nine students. Observation, interviews, and the USE Questionnaire were administered. Revisions based on pilot findings produced Prototype III. Prototype III was tested in the First Field Trial with 33 students. Observation, interviews, the USE Questionnaire, formative tests, and a summative critical and creative thinking test were administered. Revisions based on First Field Trial results produced Prototype IV, which was tested in the Second Field Trial with 28 students using the same battery of instruments.

DATA ANALYSIS

Validity data from expert validation were analyzed by computing average scores for each aspect. The e-module was classified as Valid ($3.40 < \bar{x} \leq 4.20$) or Highly Valid ($4.20 < \bar{x} \leq 5.00$) based on established criteria (Laksana, 2024).

Practicality data were analyzed using percentage scores from the USE Questionnaire: scores of 61%-80% indicated Practical, and scores above 80% indicated Highly Practical. Observation scores were classified as Good ($0.60 < \bar{x} \leq 0.80$) or Very Good ($\bar{x} > 0.80$). Interview data were analyzed thematically using the five-step procedure described in the Instruments section.

Effectiveness was evaluated using the minimum mastery criterion of ≥ 80 for both critical and creative thinking test scores. For each trial, descriptive statistics were computed, including the mean (M), standard deviation (SD), and 95% confidence intervals (CI) calculated as $M \pm (t^* \times SD / \sqrt{n})$, where t^* is the critical t-value for $df = n - 1$ at $\alpha = 0.05$. Because the First Field Trial ($n = 33$) and Second Field Trial ($n = 28$) comprised different, non-overlapping cohorts of students rather than repeated measurements on the same individuals, the statistical significance of improvement between trials was assessed using an independent-samples t-test. Given the unequal group sizes and modestly unequal variances between trials, Welch's t-test (which does not assume homogeneity of variance) was used,

with degrees of freedom adjusted using the Welch-Satterthwaite equation. Levene's test was used to evaluate the equality-of-variance assumption. Cohen's *d* was calculated as the effect size measure using the pooled standard deviation of the two independent groups. The percentage of students meeting the mastery criterion was also calculated for each trial to provide a complementary indicator of instructional effectiveness.

RESULTS

This study produced a VR–AI integrated Business Mathematics e-module consisting of eight learning units. Each unit presents real-world business and mathematical problems through 360° VR simulations, featuring AI-powered virtual characters with realistic visuals, facial expressions, body movements, and contextually appropriate dialogue. The e-module is accessible via smartphones, laptops, and tablets. Findings are presented according to the three research questions: validity, practicality, and effectiveness.

PRELIMINARY INVESTIGATION

The needs and context analysis revealed that existing Business Mathematics learning materials did not systematically support the development of critical or creative thinking. Instruction was predominantly teacher-centered, with minimal opportunities for contextual or applied problem-solving. A diagnostic assessment administered in the preceding academic year confirmed that fewer than 48% of students achieved the minimum mastery criterion on higher-order thinking tasks, with a cohort mean of 67.4. Eight core topics were identified through curriculum analysis and subsequently developed into VR-based learning scenarios within the e-module.

PROTOTYPE DEVELOPMENT AND VALIDITY

Prototype I was developed following PBL syntax and submitted for expert validation using the LORI instrument. This product-level validation is distinct from the earlier instrument-validation stage: whereas the LORI, USE Questionnaire, observation sheet, interview guides, and essay tests were each content-validated by the panel of five expert judges (Section on Instruments) before data collection, the LORI instrument was then applied by a separate panel of three subject-specific validators to rate the e-module prototype itself, one validator per aspect (content, design, and media). Results are presented in Tables 1, 2, and 3.

The validation results confirm that all three aspects of the e-module achieved Highly Valid status. For learning design, the mean of 4.40 (*SD* = 0.29) reflects high quality across four indicator dimensions: visual layout and readability (items 1–3), content relevance and PBL integration (items 4–7), VR integration quality and accessibility (items 8–11), and critical and creative thinking development (items 12–14). Expert 3 gave the highest rating of 4.71, with consistent agreement that the instructional sequence (from VR-based problem orientation through investigation, discussion, presentation, and reflection) meets strong pedagogical standards. For media quality, the mean of 4.42 (*SD* = 0.32) reflects strong ratings across five indicator clusters: interface design and readability (items 1–4), graphics, audio, and animation quality (items 5–8), device compatibility and navigation (items 9–10), VR and AI technology integration (items 11–13), and thinking skill support (items 14–16). The AI integration indicator (item 12) and the concept comprehension relevance indicator (item 13) received high ratings from all three validators, confirming that AI facilitation within VR was judged as effective and purposeful. For content, the mean of 4.57 (*SD* = 0.05), the highest and most consistent score across all validation aspects, reflects strong ratings across 21 items encompassing curriculum alignment, systematic presentation, PBL integration, cultivation of critical and creative thinking, language clarity, motivational design, and provisions for independent learning. All three content validators awarded the maximum score (5) for learning objective accuracy, cultivation of critical and creative thinking, and support for student autonomy. Expert feedback was incorporated through systematic revisions, culminating in Prototype II.

Table 1. Learning design validation results

No.	Validator	Design validation score	SD	Category
1.	Expert 1 (Design Specialist)	4.14	—	Valid
2.	Expert 2 (Instructional Technology)	4.36	—	Highly Valid
3.	Expert 3 (Educational Design)	4.71	—	Highly Valid
	Average Design Validation	4.40	0.29	Highly Valid

Table 2. Learning media validation results

No.	Validator	Media validation score	SD	Category
1.	Expert 1 (Media Technology)	4.06	—	Valid
2.	Expert 2 (Educational Technology)	4.50	—	Highly Valid
3.	Expert 3 (Digital Media)	4.69	—	Highly Valid
	Average Media Validation	4.42	0.32	Highly Valid

Table 3. Content validation results

No.	Validator	Content validation score	SD	Category
1.	Expert 1 (Business Mathematics)	4.57	—	Highly Valid
2.	Expert 2 (Mathematics Education)	4.52	—	Highly Valid
3.	Expert 3 (Business Education)	4.62	—	Highly Valid
	Average Content Validation	4.57	0.05	Highly Valid

PRACTICALITY RESULTS

Practicality was assessed across three trials through observation, interviews, and the USE Questionnaire.

Pilot test (Prototype II)

Nine students participated. Observation yielded a mean score of 0.77 (Good; $0.60 < \bar{x} \leq 0.80$), with a mean per-respondent score of 3.84 out of 5.00 and a per-module score of 73 for the single module assessed. USE Questionnaire results were: Usefulness, 83.81%; Ease of Use, 85.56%; Ease of Learning, 86.22%; Satisfaction, 83.56%; and Overall, 84.66% (Highly Practical). The relatively high pilot score reflects the small, purposively selected sample of nine students (three from each achievement level) rather than a fully representative class; the subsequent decline in overall USE score in the First Field Trial (72.17%, $n = 33$) is expected, as a larger and more heterogeneous participant group naturally produces more varied aggregate ratings. Interview data yielded substantive qualitative insights. Students reported that the 360° VR environment made previously abstract business mathematics concepts more concrete and accessible. Student S1 noted that the visualized business environment

provided a clearer practical picture, while S2 described the immersive effect as making abstract mathematical concepts feel genuine and real. Several students encountered initial adaptation challenges: difficulty in navigating VR view control and button selection was commonly reported, though most resolved these difficulties after a few attempts. Students S1 and S4 specifically recommended that a step-by-step VR usage guide be included at the beginning of the module. Students also requested more practice items and suggested adding subtitles to VR dialogues for better information clarity. These findings informed targeted revisions for Prototype III. Figure 2 presents the main menu interface of the e-module, and Figure 3 illustrates a representative VR simulation scenario.

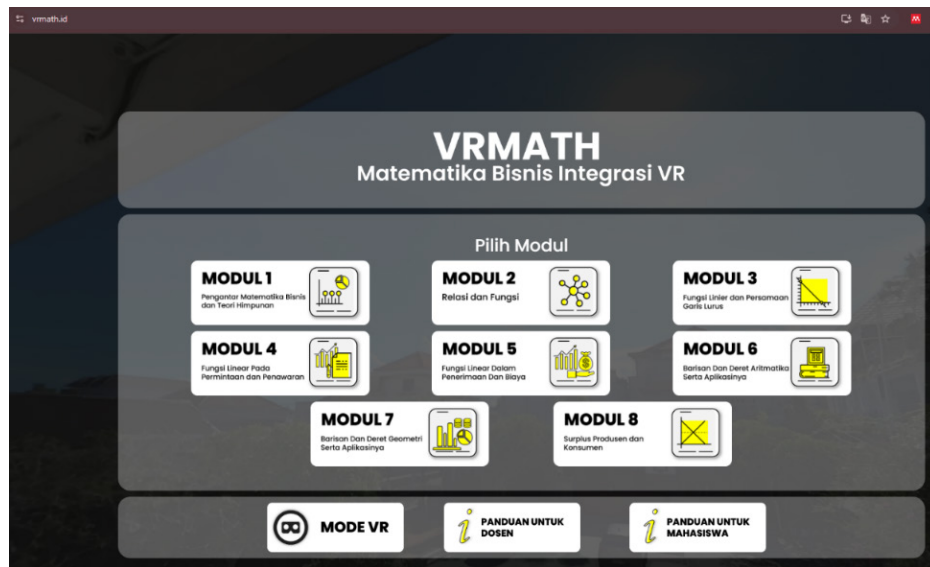


Figure 2. Main menu of the VR–AI integrated business mathematics e-module

The main menu provides access to all eight thematic learning chapters. The application is internet-accessible and compatible with multiple devices, including smartphones, laptops, and tablets. Figure 3 depicts a representative VR simulation of a Sales Department business scenario, in which AI-generated characters engage in contextualized business dialogue while students observe, analyze, and interact with the environment.

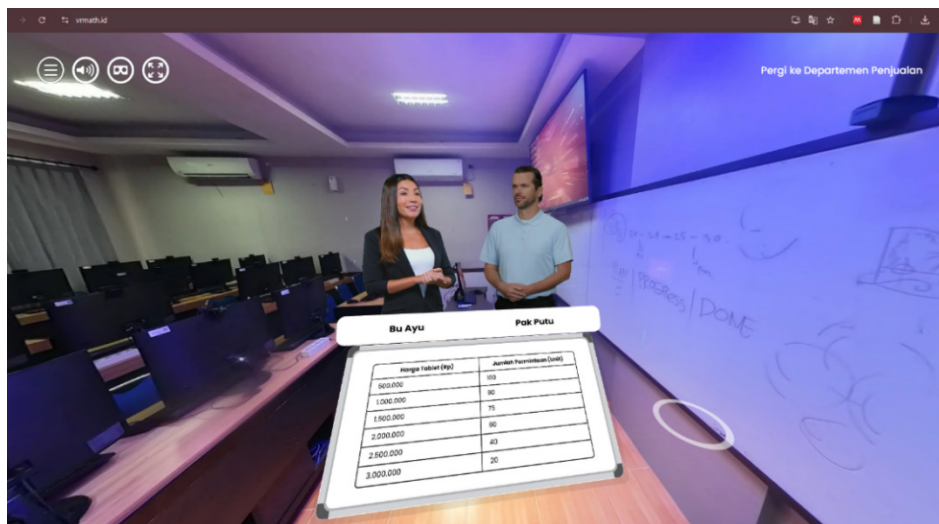


Figure 3. Sales department simulation in the VR–AI integrated e-module

First field trial (Prototype III)

Thirty-three students participated. Observation produced a mean score of 0.84 (Very Good; $\bar{x} > 0.80$), with a mean per-respondent score of 4.22 and per-module scores ranging from 68 (Module 1) to 88 (Modules 7 and 8), reflecting progressive improvement in learning implementation quality across the sequence. USE Questionnaire results were Usefulness 71.61% (score: 777/1085), Ease of Use 73.06% (score: 453/620), Ease of Learning 72.90% (score: 565/775), Satisfaction 71.48% (score: 554/775), and Overall 72.17% (score: 2349/3255), classified as Practical. Interview data revealed four consistent themes. First, students reported a shift toward more systematic reasoning: S1 stated that the most noticeable change was greater awareness of their own thinking process, reasoning about whether a method was truly relevant before applying it, rather than applying formulas directly. Second, VR simulations prompted strategy revision: S2 confirmed that after viewing the simulation, they recognized that a mathematically correct strategy is not always contextually appropriate in a business setting, prompting a change of approach. Third, collaborative discussion consistently stimulated creative ideation: S4 noted that group discussion generated many new ideas worth trying, and S1 observed that discussion enriched their perspective and deepened the quality of solutions. Fourth, business simulation videos accompanied by analytical questions were consistently identified as the most influential VR component for the development of critical and creative thinking. Challenges persisted for some students: S7 reported difficulty translating VR visual scenarios into calculation steps, while S8 acknowledged still tending to search for a formula before reading the problem carefully. These nuanced responses informed further refinements for Prototype IV.

Second field trial (Prototype IV).

Twenty-eight students participated. Following targeted revisions, including the addition of a VR navigation tutorial, enhanced visual elements, and additional practice items, substantial improvements were observed across all indicators. Observation yielded a mean score of 0.92 (Very Good; $\bar{x} > 0.80$), with a mean per-respondent score of 4.61 and per-module scores ranging from 85 (Modules 1 and 2) to 91 (Module 8), reflecting consistently high-quality implementation throughout the entire learning sequence. USE Questionnaire results were: Usefulness 86.12% (score: 844/980), Ease of Use 87.32% (score: 489/560), Ease of Learning 86.71% (score: 607/700), Satisfaction 85.71% (score: 600/700), and Overall 86.39% (score: 2540/2940), classified as Highly Practical. Interview data from the Second Field Trial reflected a qualitative shift in student responses. Students described greater confidence in applying analytical strategies: “VR makes learning more engaging, interactive, and enjoyable – I feel more motivated and enthusiastic” (S8) and “The combination is very complementary: the e-module provides the theoretical foundation while VR reinforces understanding through visualization and concrete simulation” (S1). Students in the Second Field Trial demonstrated notably deeper reflective awareness: S1 explained that they no longer focused directly on formulas; instead, they began with a contextual understanding, identified key information, and considered relationships between data points before selecting a solution approach. S2 described having developed greater openness and flexibility, consistently weighing multiple possible solutions rather than settling on a single answer. Students consistently reported that AI-facilitated interactions prompted them to evaluate assumptions, consider alternative solutions, and reflect on the logical basis of their reasoning.

EFFECTIVENESS RESULTS

Effectiveness was evaluated through formative tests during learning activities and summative assessments of critical and creative thinking skills following the completion of each field trial. Descriptive statistics for all effectiveness measures are presented in Table 4.

In the First Field Trial, the formative test yielded a mean of 83.57 (SD = 6.24, 95% CI [81.36, 85.78]), indicating adequate mastery of course content. The summative critical thinking test produced $M = 88.38$ (SD = 5.12, 95% CI [86.56, 90.20]), and the creative thinking test produced $M = 88.28$ (SD = 5.34, 95% CI [86.39, 90.17]). Both results exceeded the minimum mastery criterion of 80, with 87.88% of students meeting the criterion for critical thinking and 84.85% for creative thinking.

In the Second Field Trial, the formative test mean improved to $M = 88.47$ ($SD = 5.31$, 95% CI [86.41, 90.53]). The summative critical thinking test mean rose to $M = 93.42$ ($SD = 4.18$, 95% CI [91.80, 95.04]), and the creative thinking test mean rose to $M = 92.86$ ($SD = 4.05$, 95% CI [91.29, 94.43]). The percentage of students meeting the mastery criterion increased to 96.43% for critical thinking and 92.86% for creative thinking, both substantially above the 80% criterion.

Table 4. Descriptive statistics and 95% confidence intervals for effectiveness measures

Measure	Trial	n	M	95% CI	SD	% ≥ 80
Formative Test	First Field Trial	33	83.57	[81.36, 85.78]	6.24	—
Formative Test	Second Field Trial	28	88.47	[86.41, 90.53]	5.31	—
Critical Thinking	First Field Trial	33	88.38	[86.56, 90.20]	5.12	87.88%
Critical Thinking	Second Field Trial	28	93.42	[91.80, 95.04]	4.18	96.43%
Creative Thinking	First Field Trial	33	88.28	[86.39, 90.17]	5.34	84.85%
Creative Thinking	Second Field Trial	28	92.86	[91.29, 94.43]	4.05	92.86%

An independent-samples Welch's t-test confirmed that the improvement in critical thinking between field trials was statistically significant: $t(58.93) = 4.23$, $p < .001$, Cohen's $d = 1.07$, 95% CI for the mean difference [2.66, 7.42]. Levene's test indicated no significant violation of the equal-variance assumption, $F = 1.50$, ns. The improvement in creative thinking was similarly significant: $t(58.32) = 3.80$, $p < .001$, Cohen's $d = 0.96$, 95% CI for the mean difference [2.17, 6.99] (Levene's $F = 1.74$, ns). Both effect sizes fall in the large range ($d > 0.80$), reflecting the practical significance of iterative prototype refinements. Figure 4 presents a visual comparison of mean critical and creative thinking scores across the two field trials.

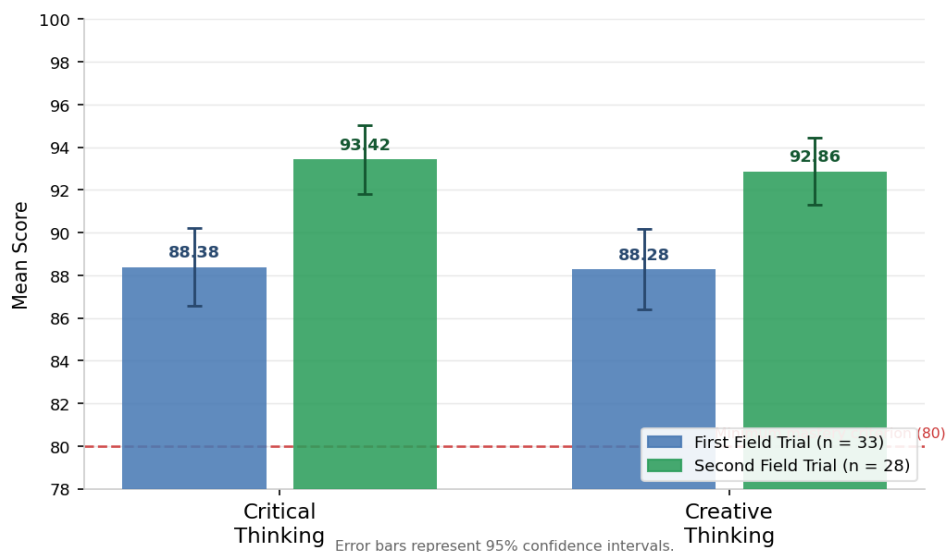


Figure 4. Comparison of mean critical and creative thinking scores: first field trial vs. second field trial

Note. Error bars represent 95% confidence intervals; dashed line indicates the minimum mastery criterion (score = 80).

Critical thinking improved by 5.04 points (from 88.38 to 93.42), and creative thinking improved by 4.58 points (from 88.28 to 92.86). USE Questionnaire scores showed a consistent upward trend across all four dimensions between trials: usefulness increased from 71.61% to 86.12%, ease of use from 73.06% to 87.32%, ease of learning from 72.90% to 86.71%, and satisfaction from 71.48% to 85.71%. These gains collectively reflect both the impact of prototype refinements and the cumulative effect of sustained engagement with the VR–AI integrated learning environment. Taken together, the e-module fulfills the criteria of being valid, practical, and effective.

DISCUSSION

The results of this study demonstrate that the VR–AI integrated Business Mathematics e-module meets established standards of validity, practicality, and effectiveness. These findings are interpreted here through relevant theoretical frameworks to explain not simply that the module works, but why and how the integration of VR and AI produced the observed outcomes.

The high validity ratings across learning design ($M = 4.40$, $SD = 0.29$), media ($M = 4.42$, $SD = 0.32$), and content ($M = 4.57$, $SD = 0.05$) reflect the coherence between the module’s instructional architecture and established pedagogical standards. From a constructivist perspective, the PBL-structured learning sequence, in which VR problem orientations precede individual investigation, group discussion, solution presentation, and reflection, mirrors the conditions under which learners construct meaningful knowledge through active engagement with authentic contexts (Makransky & Petersen, 2021). Kolb’s (1984) experiential learning theory further supports this design. The VR simulations function as concrete experiences that enable learners to move through cycles of observation, conceptualization, and active experimentation; precisely the sequence required for deep comprehension of business mathematics phenomena. The CAMIL framework additionally explains why the immersive, 360° VR environment was rated highly for engagement potential: simultaneous cognitive and affective stimulation during business scenario interactions creates conditions for deeper information processing and more durable schema formation (Makransky & Petersen, 2021). These results are consistent with Ravichandran and Mahapatra (2023) and Rong et al. (2022), who documented similar enhancements in conceptual understanding and creative cognition through VR-based learning.

The improvement in practicality from 72.17% in the First Field Trial to 86.39% in the Second Field Trial, driven primarily by enhancements to VR navigation guidance, interface clarity, and content variety, reflects both the effectiveness of iterative DBR refinement and the adaptability of the learning design. Student interview responses from both trials consistently identified the VR simulations and AI-facilitated discussion questions as the most influential features for thinking development. In the First Field Trial, student S1 observed: “The business simulation videos and analytical questions were highly influential because they required me to understand the context fully, evaluate data, and compare alternative solutions.” In the Second Field Trial, student S2 noted: “VR made me realize that a mathematically correct strategy may not be contextually appropriate in a business setting, so I adjusted my approach.” These qualitative findings align with Technology Acceptance Model (TAM) predictions that perceived usefulness and ease of use are the primary determinants of technology adoption in learning contexts (Faisal & Dharmaraj, 2024).

The effectiveness results indicate substantively strong learning outcomes. The observed progression from 88.38 to 93.42 for critical thinking ($d = 1.07$) and from 88.28 to 92.86 for creative thinking ($d = 0.96$) between field trials reflects the benefit of systematic prototype refinement guided by formative evaluation data. These outcomes exceed those reported in comparable studies: Rong et al. (2022) found significant but more modest gains in creative cognition with AI and VR combined, while Eka-yana et al. (2024, 2025) documented improvements in creative thinking through project-based STEAM learning, though without VR integration. The present study’s results, therefore, represent an advance in terms of the magnitude and consistency of HOTS development attributable to integrated VR–AI instruction.

The specific contribution of AI to observed learning outcomes merits careful analysis. Within the VR environment, AI characters functioned not merely as narrators but as adaptive facilitators: they posed contextually situated questions that prompted students to identify assumptions, evaluate data, and generate alternative solutions. This scaffolding function aligns with self-regulated learning theory, which holds that external prompting supports students in developing metacognitive monitoring skills and adaptive strategy use (Suharta et al., 2025). Student S1 from the Second Field Trial articulated this explicitly: “I became more aware of my own thinking process. I no longer applied formulas directly, but reasoned first about whether the method was truly relevant to the data and goals of the problem.” This metacognitive shift is a hallmark of effective higher-order thinking development and distinguishes the VR–AI integrated approach from purely content-delivery technologies.

Compared to studies reporting only modest gains from VR without AI facilitation, such as Bachiller et al. (2023) in heritage museum education and Cho and Park (2023) in environmental science, the present study’s results suggest that AI-mediated interaction within VR environments may be a critical ingredient for activating the analytical and evaluative cognitive processes associated with critical thinking. This interpretation is further supported by Makransky and Lilleholt (2018), who found that immersive VR alone could increase cognitive load without improving learning when pedagogical scaffolding was absent. In the present study, the AI facilitation layer appeared to mitigate this risk by structuring the learner’s interaction with the VR environment through guided questioning and adaptive feedback. Similarly, Huang et al. (2023) demonstrated that AI-driven feedback is most effective when embedded within a broader pedagogical structure that supports metacognitive development — a condition fulfilled by the PBL framework in this study. These contrasting findings underscore that neither VR nor AI alone is sufficient; their integration within a coherent pedagogical design appears to be the mechanism through which higher-order thinking gains are achieved.

Several limitations must be acknowledged. First, participants were drawn exclusively from a single study program at a single institution, limiting the generalizability of the findings to other educational contexts. Second, technical barriers to VR implementation persisted across both field trials, with some students reporting initial disorientation and control difficulties. Third, this study did not employ a control group, making it impossible to attribute learning gains exclusively to the VR–AI intervention rather than to PBL instruction more broadly. Fourth, the sample sizes, particularly in the Second Field Trial ($n = 28$), limit the statistical power to detect differential effects across student subgroups. These limitations should inform the design of future investigations.

From a pedagogical perspective, the findings suggest several practical implications. Higher education institutions implementing VR–AI integrated modules should provide systematic technical orientation sessions prior to instructional use to mitigate initial adaptation challenges. Instructional designers should ensure that AI-facilitated prompts are explicitly calibrated to target higher-order thinking indicators rather than knowledge recall. Curriculum developers should consider the sequential integration of VR simulations with AI-guided discussion as a replicable design pattern applicable across mathematics and related disciplines. Institutional administrators should plan for the technical infrastructure requirements of multi-device VR deployment, including reliable internet connectivity and device availability.

CONCLUSION

This study demonstrates that a VR–AI integrated Business Mathematics e-module, developed using the PLOMP design model and grounded in PBL pedagogy and constructivist learning theory, meets rigorous standards of validity, practicality, and effectiveness in higher education. The study’s principal contribution is an empirically validated framework for integrating 360° VR simulations with AI-facilitated adaptive interaction within a structured instructional sequence specifically designed to develop critical and creative thinking in business mathematics.

The e-module achieved high validity across learning design ($M = 4.40$, $SD = 0.29$), media ($M = 4.42$, $SD = 0.32$), and content ($M = 4.57$, $SD = 0.05$), all categorized as Highly Valid. Practical usability improved from 72.17% to 86.39% across field trials through iterative DBR refinement. Students' mean critical thinking scores improved from 88.38 (95% CI [86.56, 90.20]) to 93.42 (95% CI [91.80, 95.04]) and mean creative thinking scores from 88.28 (95% CI [86.39, 90.17]) to 92.86 (95% CI [91.29, 94.43]); both substantially exceeding the minimum mastery criterion of 80. The improvements were statistically significant with large effect sizes, assessed via an independent-samples Welch's t-test appropriate to the non-overlapping First and Second Field Trial cohorts: $t(58.93) = 4.23$, $p < .001$, $d = 1.07$ for critical thinking; and $t(58.32) = 3.80$, $p < .001$, $d = 0.96$ for creative thinking.

Two limitations are particularly important for future researchers to address. First, restricting to a single study program at a single institution limits generalizability; broader, multi-institutional studies are needed to confirm the framework's applicability across diverse educational contexts. Second, the absence of a control group precludes causal attribution; future research should employ quasi-experimental or randomized designs to isolate the specific contributions of VR and AI components to observed learning gains. Future studies should also explore the scalability of this approach to different subject domains and student populations, examine long-term retention of critical and creative competencies developed through VR–AI instruction, and develop more diverse assessment instruments aligned with evolving twenty-first-century skills frameworks.

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