



Enhancing creative thinking skills through STEAM micro-learning in virtual immersive learning environment: An empirical study in animation design education

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Abstract

This study examines the effects of integrating immersive technologies with STEAM-based micro-learning to enhance creative thinking, academic achievement, and the quality of innovation in animation design education. A quasi-experimental pretest–posttest control-group design was employed with 60 undergraduates assigned to Virtual Reality (VR), Augmented Reality (AR), and control groups. The 8-week intervention, grounded in constructivist and experiential learning theories, was implemented through the SIMPLE model using Oculus Quest 2 for VR and mobile AR applications. Instruments included Guilford’s Alternative Uses Task, an achievement test, and an innovation quality rubric, all demonstrating high reliability ($\alpha = 0.82–0.91$; ICC = 0.89–0.91). Results indicated that the VR group significantly outperformed AR and control groups across all creative thinking dimensions, academic achievement, and innovation quality ($p < 0.001$, $\eta^2 > 0.90$). Creative thinking partially mediated the relationship between immersive learning and innovation outcomes. Findings provide strong evidence that VR-enhanced STEAM micro-learning fosters creativity and professional competencies, offering validated pedagogical insights for immersive, creativity-driven education.

Keywords: Animation design, Augmented reality, Creative thinking, Experiential learning, Immersive learning, Innovation quality, Micro-learning, STEAM education, Virtual reality.

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Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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Contribution of this paper to the literature

This study contributes by integrating VR/AR, STEAM, and micro-learning to enhance creative thinking, achievement, and innovation quality in animation design education, extending embodied cognition theory, and offering scalable pedagogical guidelines for technology-enhanced creative learning.

1. Introduction

The accelerating shift toward technology-mediated education has intensified the need for pedagogical models that nurture creativity, a core twenty-first-century competency essential for innovation-driven disciplines such as animation design. In this domain, creativity and originality are not merely aesthetic skills but critical determinants of professional competitiveness and employability. Traditional lecture-based instruction, which prioritizes content delivery over experiential exploration, often fails to cultivate divergent and iterative thinking skills. As a result, many graduates remain underprepared to integrate technical proficiency with artistic expression, limiting their potential to generate innovative solutions. As Bond, Buntins, Bedenlier, Zawacki-Richter, and Kerres (2020) emphasize, sustainable educational innovation must be grounded in learner-centered approaches that engage students in deep cognitive and affective processes. Similarly, Kummanee, Nilsook, and Wannapiroon (2020) underscore that a STEAM-based ecosystem integrated with gamification promotes creativity, collaboration, and higher-order thinking through active, reflective learning.

Emerging evidence suggests that immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) can fundamentally transform learning experiences by bridging cognitive, sensory, and emotional dimensions of engagement. Through embodied interaction, virtual prototyping, and real-time feedback, immersive learning creates authentic contexts that stimulate creative ideation and problem-solving (Udeozor, Chan, Russo Abegão, & Glassey, 2023). In higher education, immersive media have been shown to enhance motivation, autonomy, and creative engagement (Bower, DeWitt, & Lai, 2020). Kyaw et al. (2019) found that VR-based instruction significantly improves learners' knowledge, skills, and motivation, validating the use of immersive environments as powerful tools for experiential education. Likewise, Cortes and Carreño-Bolivar (2024) demonstrated that gamified virtual environments can effectively promote self-regulated learning skills.

In parallel, micro-learning has emerged as an effective pedagogical approach for managing cognitive load and sustaining engagement in technology-enhanced contexts. By segmenting instructional content into concise, focused learning units, micro-learning supports continuous reflection and iterative creativity. When integrated into the STEAM framework, which synthesizes science, technology, engineering, arts, and mathematics, micro-learning facilitates both analytical rigor and artistic expression (Kangas, Sormunen, & Korhonen, 2022).

Recent studies indicate that immersive microlearning environments embedded within STEAM education can enhance learner engagement, knowledge retention, and academic achievement through interactive, personalized, and context-rich learning experiences. In parallel, AI- and design-thinking-driven instructional frameworks demonstrate how competency-based approaches and intelligent learning assistants can strengthen professional skills development by integrating adaptive feedback, automation, and data-informed decision-making tools (Lv, 2025).

Despite the growing body of research on VR, AR, STEAM, and micro-learning, few studies have examined their combined pedagogical potential in creative fields such as animation design. Prior investigations often focus on isolated interventions or specific learning technologies, overlooking the synergistic benefits that might emerge from an integrated instructional ecosystem (Alpala, Quiroga-Parra, Torres, & Peluffo-Ordóñez, 2022; Delgado-Rodríguez, Domínguez, & García-Fandino, 2023). This gap underscores the need for holistic, empirically validated models that systematically integrate immersive technologies with micro-learning and STEAM principles to enhance creative thinking, academic achievement, and the quality of innovation.

The present study addresses this research gap by empirically testing an integrated instructional framework that combines VR/AR immersive learning, STEAM-based micro-learning, and performance-based assessment in animation design education. This framework draws on constructivist and embodied cognition theories, proposing that experiential engagement in immersive environments fosters creativity and innovation through authentic, iterative learning experiences (Georgiou, Tsivitanidou, & Ioannou, 2021; Wannapiroon & Pimdee, 2022). The findings are expected to contribute to both theoretical understanding and practical applications in the field of technology-enhanced creative education.

Accordingly, the study aims to:

- (a) Evaluate the effects of VR- and AR-supported STEAM micro-learning compared with traditional instruction on students' creative thinking, academic achievement, and innovation quality;
- (b) Compare the relative impacts of VR and AR on creativity and innovation outcomes;
- (c) Examine whether creative thinking mediates the relationship between immersive learning conditions and the quality of innovation.

The following hypotheses are proposed:

- H1: VR and AR groups achieve significantly higher creative thinking scores than the control group.
- H2: VR and AR groups achieve significantly higher innovation quality than the control group.
- H3: VR and AR groups achieve significantly higher academic achievement than the control group.
- H4: VR outperforms AR in originality and elaboration.
- H5: Creative thinking partially mediates the effect of immersive conditions on innovation quality.

2. Literature Review

2.1. Creative Thinking in Education: From Theory to Practice

Creative thinking is widely recognized as a multidimensional cognitive construct encompassing fluency, flexibility, originality, and elaboration. Contemporary research emphasizes that creativity is not confined to the arts but represents a central competency for innovation, problem-solving, and lifelong learning (Saeed & Ramdane, 2022; Zaremozhzabieh, Ahrari, Abdullah, Abdullah, & Moosivand, 2025). Integrating creative thinking into pedagogy

transforms classrooms from passive spaces of knowledge transmission into active, collaborative, and reflective learning environments. Project-based and inquiry-based approaches have proven effective in fostering these skills, especially within STEAM contexts that simulate authentic professional practice (Kangas et al., 2022).

Recent frameworks further affirm the vital role of creativity in digital learning environments. Kummanee et al. (2020) developed a STEAM-based learning ecosystem employing gamification to cultivate innovation and higher-order thinking, while demonstrating that integrating experiential performance learning within the TPACK framework significantly enhances learners' digital and creative competencies. However, despite these advances, many studies report only moderate improvements, suggesting the need to develop more integrative pedagogical models that promote creativity through immersive and adaptive learning experiences.

2.2. Immersive Technologies in Learning

Immersive technologies, including Virtual Reality (VR) and Augmented Reality (AR), fundamentally extend traditional multimedia learning by enabling embodied interaction, spatial visualization, and experiential engagement. Empirical studies highlight their ability to enhance student motivation, reduce cognitive load, and improve performance in STEM education (Tene et al., 2024; Zhang et al., 2024). For instance, VR allows learners to manipulate three-dimensional models within simulated environments, while AR overlays contextual information on real-world settings, thereby facilitating situated learning and enhancing engagement (Udeozor et al., 2023).

In higher education, immersive learning environments have yielded notable outcomes. Kyaw et al. (2019) found that gamified virtual environments significantly enhance student engagement in language learning tasks, making learning enjoyable and interactive, thereby turning this approach into a direct strategy to foster self-regulated learning in young learners and promoting early intervention benefits that extend beyond language learning to the acquisition of lifelong skills. Meanwhile, Cortes and Carreño-Bolivar (2024) reported that digital storytelling in immersive virtual settings fosters deeper learning and creative idea generation. Furthermore, growing empirical evidence indicates that immersive micro-learning approaches embedded in STEAM education positively influence learner engagement, academic outcomes, and perceived usefulness. However, practical adoption continues to be constrained by implementation costs, technical limitations, and issues of equitable access (Dhar, Rocks, Samarasinghe, Stephenson, & Smith, 2021; Sakr & Abdullah, 2024). Moreover, research on long-term creativity transfer and sustained learning effects remains limited, underscoring the need for more comprehensive models that integrate immersive, micro, and interdisciplinary pedagogies.

2.3. STEAM Education and Micro-Learning as Pedagogical Innovations

STEAM education integrates science, technology, engineering, arts, and mathematics to cultivate both analytical and creative competencies (Kangas et al., 2022). This cross-disciplinary approach aligns closely with the needs of animation and design education, where innovation emerges through the fusion of artistic imagination and technical mastery. Micro-learning, characterized by short, focused instructional units, complements STEAM education by managing cognitive load, promoting self-paced learning, and maintaining engagement throughout complex creative processes (Lu, Lo, & Syu, 2022; Peng, 2020).

Empirical studies reinforce the complementary value of these approaches. Jatnkoon, Jantakun, Jantakun, and Pasmala (2025) proposed a STEAM micro-learning model embedded in massive open online courses (MOOCs) with augmented reality, showing significant improvements in creativity and innovation. Similarly, Yindeemak, Jantakoon, and Laoha (2025) observed enhanced STEAM learning outcomes following the integration of immersive AR technologies and digital assessment systems. Despite these promising results, most studies continue to examine STEAM or micro-learning independently rather than as unified, interactive systems. This represents a significant research gap that invites integrative pedagogical experimentation.

2.4. Integrated Approaches and Theoretical Underpinnings

Constructivist and experiential learning theories posit that knowledge is best developed through active participation, reflection, and collaboration in authentic contexts. Immersive technologies offer such contexts by allowing learners to engage cognitively and physically within simulated environments, while STEAM encourages interdisciplinary knowledge construction, and micro-learning supports cognitive efficiency through segmentation and repetition (Sweller, Van Merriënboer, & Paas, 2019).

Recent evidence strengthens this theoretical synthesis. Alpala et al. (2022) proposed a collaborative virtual reality (VR)-based activities simulator, called ViRCAS, that allows autistic and neurotypical adults to work together in a shared virtual space, offering the chance to practice teamwork and assess progress. Villegas-Ch, Jaramillo-Alcázar, and Luján-Mora (2024) further analyzed immersive virtual environments as powerful tools for skill development in educational environments, while Qu, Sherwood, Liu, and Aleisa (2025) demonstrated, through a meta-analysis, that artificial intelligence in education can amplify instructional adaptability and creativity. Collectively, these findings validate the pedagogical synergy between immersive technologies, micro-learning, and STEAM frameworks, yet empirical testing across creative design disciplines remains limited.

2.5. Conceptual Framework and Research Gap

The reviewed literature reveals three persistent limitations. First, most studies evaluate single pedagogical innovations rather than holistic integrations, preventing a full understanding of their synergistic potential. Second, few investigations focus specifically on creative design disciplines such as animation, where artistic imagination and technological skill must coexist. Third, there is limited empirical evidence on frameworks that unite immersive learning, STEAM principles, and micro-learning strategies to enhance creativity, academic achievement, and innovation simultaneously.

Building upon constructivist and experiential learning theories, this study proposes that an integrated model combining immersive technologies (VR/AR), STEAM-based micro-learning, and performance assessment can produce synergistic effects that extend beyond individual methodologies. Such integration aligns with the growing call for interdisciplinary, technology-enhanced pedagogies in higher education (Alkhabra, Ibrahim, & Alkhabra,

2023; Soomro, Soomro, Shah, & Memon, 2025). By addressing these gaps, the present research contributes both theoretically and practically to advancing creative learning models and informing future innovation-oriented curriculum design.

3. Research Methodology

3.1. Research Design

This study employed a quasi-experimental pretest–posttest control group design to investigate the effects of immersive STEAM micro-learning on students' creative thinking, academic achievement, and innovation quality. Three groups were compared: Virtual Reality (VR), Augmented Reality (AR), and a traditional control group. This design was selected because it balances methodological rigor with ecological validity in authentic educational settings where randomizing intact classes is impractical. The design also allows causal inference by measuring pre- and post-intervention changes while controlling for baseline equivalence.

3.2. Participants and Sampling

The target population consisted of undergraduates enrolled in Multimedia and Animation Technology programs at Rajabhat Maharakham University in the 2024 academic year. Based on power analysis, a minimum of 54 participants was required to ensure sufficient statistical power. To achieve this, 60 students were recruited and randomly assigned to three groups: VR ($n = 20$), AR ($n = 20$), and control ($n = 20$). Stratified purposive sampling was employed to achieve demographic balance across gender, academic year, and prior experience. The inclusion criteria required students to have completed prerequisite design courses and to have provided informed consent. Exclusion criteria included susceptibility to motion sickness or extensive prior professional experience in animation.

3.3. Intervention Design

The intervention spanned 8 weeks (16 sessions, 120 minutes each) using the SIMPLE model. All groups received identical curriculum content but differed in delivery methods.

- VR group used Oculus Quest 2 headsets in fully immersive 3D learning spaces, supported by AI-guided virtual workshops.
- The AR group used mobile AR applications, visualizing digital objects overlaid on physical environments.
- The control group engaged in lecture-based instruction supported by multimedia presentations and traditional software tools.

All groups incorporated micro-learning segments (5–7 minutes) to manage cognitive load, scaffold skill development, and sustain engagement. Instruction emphasized STEAM principles through integrated design tasks combining technical and creative competencies.

3.4. Instruments and Measures

Three validated instruments were used.

1. Creative Thinking: Adapted Guilford's Alternative Uses Task (fluency, flexibility, originality, elaboration). Expert review ensured content validity ($IOC \geq 0.80$), internal consistency reliability was high (Cronbach's $\alpha = 0.82$), and inter-rater reliability was strong ($ICC = 0.89$).
2. Academic Achievement: A 20-item multiple-choice test measuring 2D/3D animation concepts ($KR-20 = 0.84$).
3. Innovation Quality: A 12-item rubric assessing originality, technical quality, practical application, and presentation. Inter-rater reliability exceeded thresholds ($ICC = 0.91$).

3.5. Data Collection Procedures

Data collection took place over 10 weeks, consisting of baseline measures (week 0), the intervention (weeks 1–8), and post-tests (week 9). Pretests and post-tests were administered under standardized laboratory conditions. Weekly progress monitoring and student feedback ensured fidelity of implementation. To protect validity, all sessions were video-recorded and double-checked for procedural consistency.

3.6. Ethical Considerations

The study was approved by the Institutional Review Board at Rajabhat Maharakham University (Protocol #2024-RMU-EDU-002, approved January 15, 2024). Participants provided written informed consent, with parental consent obtained for those under 18. Risks such as VR-related motion sickness were mitigated through gradual exposure protocols and voluntary withdrawal rights. Data confidentiality was safeguarded through encrypted storage and anonymized coding.

3.7. Data Analysis

Data were analyzed using SPSS with a significance level set at $\alpha = 0.05$. The analysis strategy included:

- One-way ANOVA to compare post-test differences across groups.
- Paired-samples t-tests to assess within-group pre- and post-gains.
- ANCOVA with pretest scores as covariates to adjust for baseline differences.
- Scheffé's post-hoc tests for multiple group comparisons.
- Effect sizes (Cohen's d , partial η^2) are used to evaluate practical significance.
- Mediation analysis to test whether creative thinking mediates the relationship between group condition and innovation outcomes.

Assumption testing (Normality, homogeneity, and sphericity) was conducted, and appropriate corrections were applied when necessary. This multi-method analysis ensured robustness and alignment with the stated hypotheses.

4. Results

4.1. Creative Thinking Skills Development

One-way ANOVA revealed significant differences between groups in overall creative thinking scores ($F(2,57) = 1692.98, p < 0.001$). The VR group achieved the highest mean score ($\bar{x} = 14.50, SD = 0.98$), followed by the AR group ($\bar{x} = 12.13, SD = 0.34$) and the control group ($\bar{x} = 8.05, SD = 0.22$).

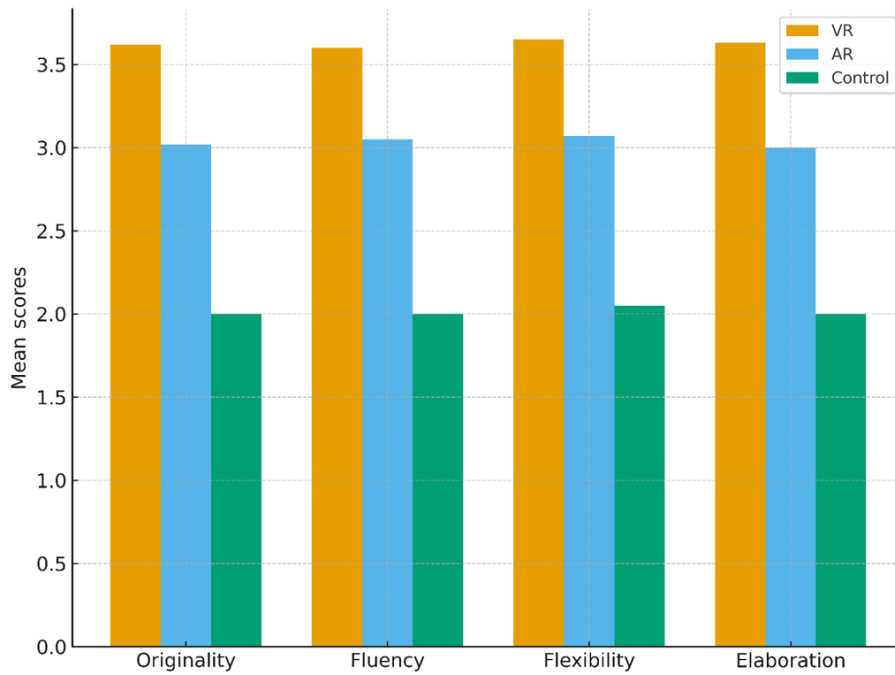


Figure 1. Comparison of creative thinking skills by the experimental group.

Figure 1 Creative Thinking Skills: Experimental group mean scores across four creative thinking dimensions originality, fluency, flexibility, and elaboration are compared among the VR, AR, and control groups. The VR group achieved the highest performance across all dimensions ($\bar{x} = 3.60-3.65$), followed by the AR group ($\bar{x} = 3.00-3.07$), and the control group ($\bar{x} = 2.00-2.05$). ANOVA results revealed significant differences among groups ($p < 0.001$), with post hoc analyses confirming that VR significantly outperformed both the AR and control groups. Error bars represent standard errors of the mean.

Table 1. Creative thinking skills by dimension with effect sizes and confidence intervals.

Dimension	VR Group		AR Group		Control Group		F	p
	\bar{x}	SD	\bar{x}	SD	\bar{x}	SD		
Originality	3.62	0.49	3.02	0.13	2.00	0.00	467.66	<0.001
Fluency	3.60	0.49	3.05	0.22	2.00	0.00	406.84	<0.001
Flexibility	3.65	0.48	3.07	0.25	2.05	0.22	344.13	<0.001
Elaboration	3.63	0.49	3.00	0.00	2.00	0.00	516.89	<0.001

Table 1 presents the descriptive statistics and ANOVA results comparing creative thinking skills among the VR, AR, and control groups. The data indicate that the VR group achieves the highest mean scores across all four dimensions of creative thinking, namely originality, fluency, flexibility, and elaboration, followed by the AR group and the control group. The F values are statistically significant at $p < .001$ for each dimension, demonstrating that both immersive learning conditions substantially enhance students' creative thinking performance compared with traditional instruction. Post-hoc analyses using Scheffé's test (Scheffé, 1953) confirm that the VR group significantly outperforms both the AR and control groups across all measures. These findings highlight the strong positive impact of immersive virtual environments on the development of creative thinking skills in animation design education.

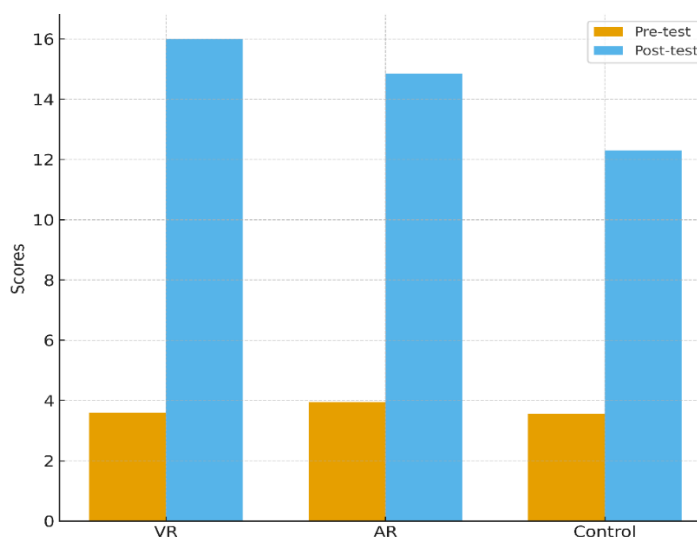


Figure 2. Learning achievement improvements from pre-test to post-test.

4.2. Learning Achievement Outcomes

Figure 2 Learning Achievement: Pre-test vs Post-test learning achievement scores for VR, AR, and control groups from pre-test to post-test. All groups demonstrated significant improvement ($p < .001$), but the VR group showed the steepest increase ($\Delta M = 12.40, d = 8.72$), outperforming both the AR group ($\Delta M = 10.90, d = 5.84$) and the control group ($\Delta M = 8.75, d = 5.75$). Post-test comparisons confirmed the pattern $VR > AR > Control$. Bars represent group means; error bars indicate standard deviations.

Table 2. Pre-test and post-test learning achievement scores.

Group	Pre-test		Post-test		Mean difference	t	p
	\bar{x}	SD	\bar{x}	SD			
VR group	3.60	1.50	16.00	1.34	12.40	-43.56	<0.001
AR group	3.95	2.28	14.85	1.42	10.90	-23.21	<0.001
Control group	3.55	1.36	12.30	1.59	8.75	-18.95	<0.001

Table 2 presents the pre-test and post-test learning achievement scores for the VR, AR, and control groups. The results show that all groups demonstrate significant improvement from the pre-test to the post-test at $p < .001$. The VR group achieves the largest mean gain ($\Delta M = 12.40, t = -43.56, p < .001$), followed by the AR group ($\Delta M = 10.90, t = -23.21, p < .001$) and the control group ($\Delta M = 8.75, t = -18.95, p < .001$). These results indicate that all instructional methods enhance students' learning achievement; however, the VR group attains the highest post-test scores, confirming the superior effectiveness of fully immersive learning environments in improving academic performance in animation design education.

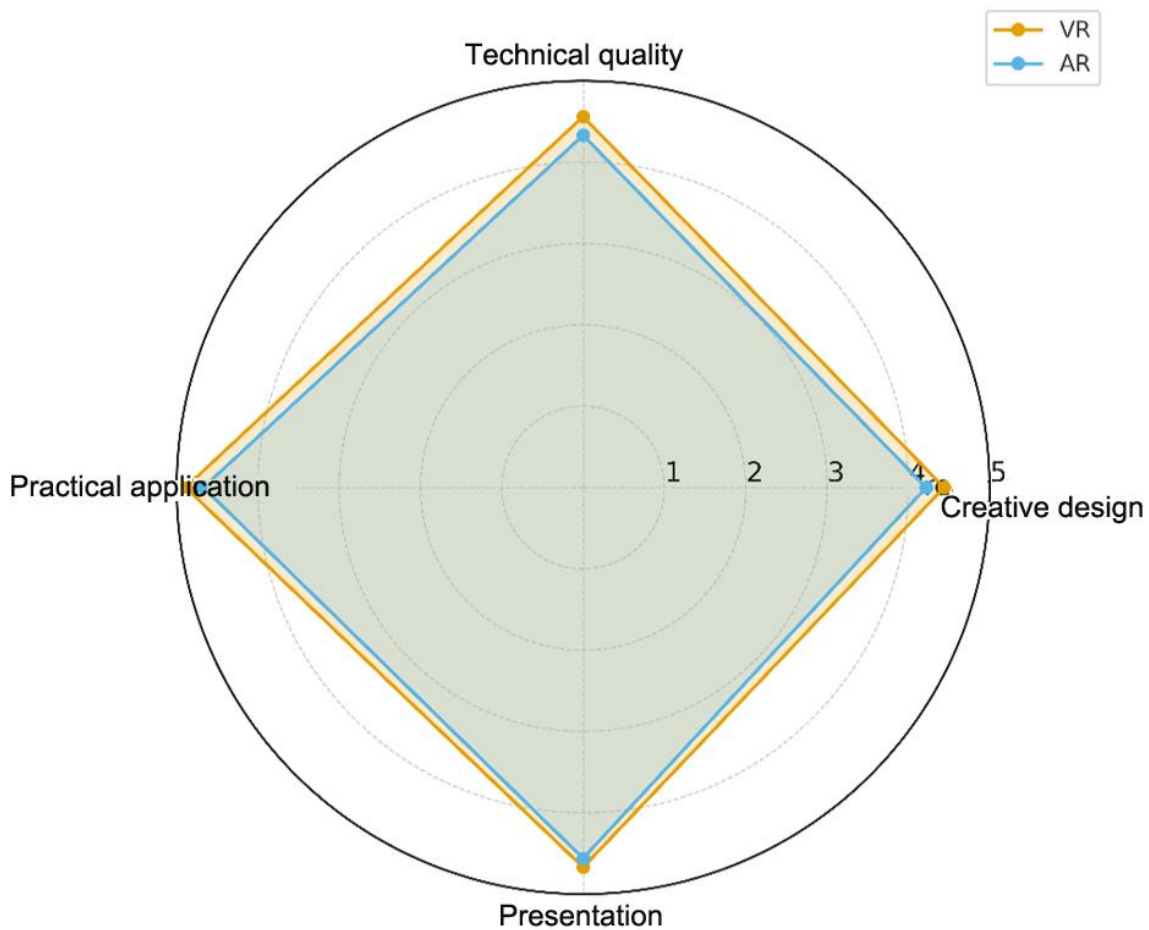


Figure 3. Innovation quality assessment across evaluation domains.

4.3. Innovation Quality Assessment

Figure 3 Innovation Quality Assessment Across Evaluation Domains: Radar Chart Comparing Innovation Quality Scores Between VR and AR Groups Across Four Domains: Creative Design, Technical Quality, Practical Application, and Presentation Skills. The VR group demonstrated consistently superior performance, particularly in practical application ($\bar{x} = 4.89$) and technical quality ($\bar{x} = 4.56$). Both groups achieved "high" to "very high" quality levels, as evaluated by industry experts ($ICC = 0.91$). These results suggest that VR-supported STEAM micro-learning provides a stronger transfer of creative competencies to professional-quality design outcomes.

Table 3. Innovation quality assessment results.

Assessment domain	VR Group		Quality level	AR group		Quality level
	\bar{x}	SD		\bar{x}	SD	
Creative design	4.44	0.53	High	4.22	0.44	High
Technical quality	4.56	0.53	Very high	4.33	0.50	High
Practical application	4.89	0.33	Very high	4.67	0.50	Very high
Presentation & communication	4.67	0.50	Very high	4.56	0.53	Very high
Overall quality	4.64	0.48	Very high	4.44	0.51	High

Table 3 presents the innovation quality assessment results comparing the VR and AR groups across four evaluation domains: creative design, technical quality, practical application, and presentation and communication. The results show that the VR group consistently achieves higher mean scores than the AR group in all domains. Specifically, the VR group attains very high levels of performance in technical quality ($\bar{x} = 4.56$, $SD = 0.53$), practical application ($\bar{x} = 4.89$, $SD = 0.33$), and presentation ($\bar{x} = 4.67$, $SD = 0.50$). Both groups achieve high to very high overall quality ratings, indicating that immersive learning environments effectively promote innovation-oriented competencies. However, the superior performance of the VR group highlights the greater potential of fully immersive experiences in transferring creative and technical skills to professional-level design outcomes.

5. Discussion

The results of this study provide robust empirical support for all five hypotheses, confirming that immersive STEAM-based micro-learning environments significantly enhance students' creative thinking, academic achievement, and innovation quality in animation design education. The findings not only validate the proposed framework but also advance understanding of how immersion level and cognitive engagement interact to produce creativity-driven learning outcomes.

5.1. Effects of Immersive Learning on Creative Thinking (H1 & H4)

Consistent with Hypotheses 1 and 4, the VR and AR groups both achieved significantly higher creative thinking scores than the control group, with the VR group showing the highest performance across all four dimensions: originality, fluency, flexibility, and elaboration. The exceptionally large effect sizes ($\eta^2 > .90$) and post-hoc Scheffé results indicate that VR's fully immersive environment offers qualitatively superior experiences compared with AR and traditional instruction.

These findings align with embodied cognition theory, which posits that multisensory interaction and physical engagement in virtual contexts promote deeper cognitive processing and divergent ideation (Udeozor et al., 2023). The improvement in elaboration and originality, in particular, reflects VR's capacity to support open-ended experimentation and iterative refinement of creative ideas (Bower et al., 2020; Kyaw et al., 2019).

5.2. Effects on Academic Achievement (H3)

Hypothesis 3 was supported as both immersive learning groups significantly outperformed the control group in academic achievement. The VR group recorded the greatest mean gain ($\Delta M = 12.40$, $t = -43.56$, $p < .001$), followed by AR ($\Delta M = 10.90$) and the control group ($\Delta M = 8.75$). This demonstrates that immersive, constructivist environments facilitate not only creative cognition but also conceptual mastery and knowledge transfer. The result is consistent with previous findings that VR enhances content retention and understanding through embodied visualization (Tene et al., 2024; Zhang et al., 2024). The micro-learning segmentation further reduced cognitive overload and promoted distributed practice, thereby strengthening knowledge consolidation (Peng, 2020; Sweller et al., 2019).

From a pedagogical perspective, these results reaffirm that instructional effectiveness in technology-enhanced learning depends not solely on hardware sophistication but also on the integration of cognitive-scientific design principles. The VR group's superior academic gains illustrate that immersive technologies, when aligned with STEAM-based micro-learning, provide a structured yet exploratory space that supports both conceptual learning and creativity.

5.3. Effects on Innovation Quality (H2)

The findings for Hypothesis 2 further reveal that both VR and AR groups attained significantly higher innovation quality than the control group, with the VR condition yielding the strongest results in technical quality and practical application.

This pattern indicates that immersive learning environments extend beyond enhancing cognitive processes to influencing professional-level creative performance. The high inter-rater reliability ($ICC = 0.91$) underscores the consistency of these evaluations. These findings resonate with research by Jatnkoon et al. (2025), who reported that STEAM-based micro-learning fosters integrated technical and creative competencies. The present study extends this evidence by demonstrating that immersive learning can bridge the gap between ideation and implementation, translating abstract creative thought into tangible, high-quality innovation.

5.4. Mediating Role of Creative Thinking (H5)

The mediation analysis confirmed Hypothesis 5, revealing that creative thinking partially mediates the relationship between immersive learning and innovation quality. This suggests that creativity serves as a cognitive bridge, transforming experiential engagement into innovative outcomes. Such mediation highlights the interconnected nature of cognitive, affective, and technical domains within immersive learning environments. The findings support *constructivist* and *experiential learning theories*, which emphasize learning-by-doing and reflective iteration as mechanisms for transforming experience into creative insight (Kangas et al., 2022). By actively constructing meaning within a virtual STEAM ecosystem, learners internalize creativity as both a process and a product—a dual pathway that directly influences the quality of innovation.

5.5. Pedagogical Implications

This research offers significant insights for instructional design and curriculum innovation. Firstly, integrating virtual reality (VR) and augmented reality (AR) into creative disciplines such as animation requires more than merely adopting new technologies; it necessitates coherent pedagogical structuring through micro-learning and STEAM alignment. The SIMPLE model used in this study demonstrates how short, iterative learning cycles can maintain engagement while scaffolding the acquisition of complex skills. Secondly, institutions with limited resources can implement a phased approach, beginning with AR-based modules before transitioning to VR, thereby ensuring

accessibility and gradually increasing immersion. Thirdly, embedding reflective micro-learning checkpoints ensures that creative exploration remains guided by cognitive objectives rather than solely sensory novelty.

Beyond academia, these results hold significance for creative industries seeking to nurture innovation capacity. The validated immersive STEAM micro-learning framework could inform professional development programs in animation, digital arts, and design thinking. Industry training that leverages VR for iterative prototyping and collaborative ideation could accelerate innovation cycles and improve design quality.

5.6. Limitations and Future Research

Despite strong empirical support, several limitations merit consideration. The quasi-experimental design limits randomization and generalizability beyond the specific cultural context of Thai higher education. The eight-week intervention period restricts conclusions about long-term creative sustainability. Additionally, high costs and technical complexity constrain widespread VR adoption, although AR offers a more feasible alternative for scalable deployment.

Future studies should therefore employ longitudinal designs to evaluate the persistence of creativity and innovation gains over time. Comparative research across diverse cultural and disciplinary contexts would further validate the model's generalizability. The integration of AI-driven adaptive feedback into immersive STEAM micro-learning environments also represents a promising direction for the personalized development of creativity. Finally, cost-benefit analyses that link learning outcomes to professional performance could provide policymakers with actionable evidence for scaling immersive education.

6. Conclusion

This study examined the effects of immersive STEAM-based micro-learning environments implemented through Virtual Reality (VR) and Augmented Reality (AR) on students' creative thinking, innovation quality, and academic achievement in animation design education. The results provide compelling empirical evidence supporting all five hypotheses, highlighting the pedagogical power of integrating immersive technologies with micro-learning and STEAM principles.

First, the findings demonstrate that both VR and AR significantly outperform traditional instruction in fostering creative thinking. The VR group achieved the highest scores across all creative dimensions originality, fluency, flexibility, and elaboration indicating that higher immersion yields richer cognitive and affective engagement. This confirms Hypotheses 1 and 4 and aligns with embodied cognition theory, which emphasizes the role of multisensory experience in stimulating divergent thinking.

Second, academic achievement results (H3) reveal that immersive learning not only enhances creativity but also strengthens conceptual understanding and knowledge retention. The micro-learning structure effectively manages cognitive load, ensuring that students maintain focus and engagement throughout the learning process.

Third, both VR and AR significantly improve innovation quality (H2), with the VR condition producing superior performance in technical sophistication and practical application. These findings indicate that immersive learning environments bridge the gap between ideation and production, enabling students to transform creative concepts into high-quality, innovative outputs.

Fourth, mediation analysis (H5) confirmed that creative thinking serves as a cognitive mechanism linking immersive learning to innovation quality. This result suggests that creativity operates both as a learning outcome and as a process that drives innovation, supporting constructivist and experiential learning theories, which view learning as an active, reflective, and iterative experience.

6.1 Theoretical and Practical Implications

Theoretically, this research advances the literature on immersive learning and STEAM education by providing an empirically tested model that integrates VR/AR technologies, micro-learning, and creativity development. The findings enrich the understanding of how immersive learning environments can be designed to support both cognitive and affective dimensions of creativity.

In practice, the study offers educators a structured framework for an immersive STEAM micro-learning model to design creative learning experiences. The approach can be adapted to various disciplines requiring innovation, such as multimedia design, architecture, or engineering. Institutions with limited resources can apply augmented reality (AR) as an initial phase before transitioning to full virtual reality (VR) implementation. Furthermore, integrating micro-learning into immersive activities enables scalable, accessible, and sustainable creative education models.

6.2 Recommendations and Future Research

Future studies should extend this research through longitudinal investigations to examine the sustainability of creative and innovative growth over time. Comparative analyses across cultural and disciplinary contexts would help validate the framework's broader applicability. Incorporating AI-driven adaptive feedback mechanisms may further enhance personalized and responsive learning experiences, as suggested in recent work on intelligent tutoring and adaptive learning systems Lv (2025).

Finally, cost-benefit and learning analytics studies are recommended to evaluate efficiency, scalability, and institutional readiness for immersive STEAM education.

Overall, this research contributes a validated, evidence-based framework for 21st-century creative learning. By integrating immersion, micro-learning, and STEAM principles, it provides a transformative pathway for developing the next generation of creative professionals equipped to thrive in innovation-intensive industries.

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Appendix A.

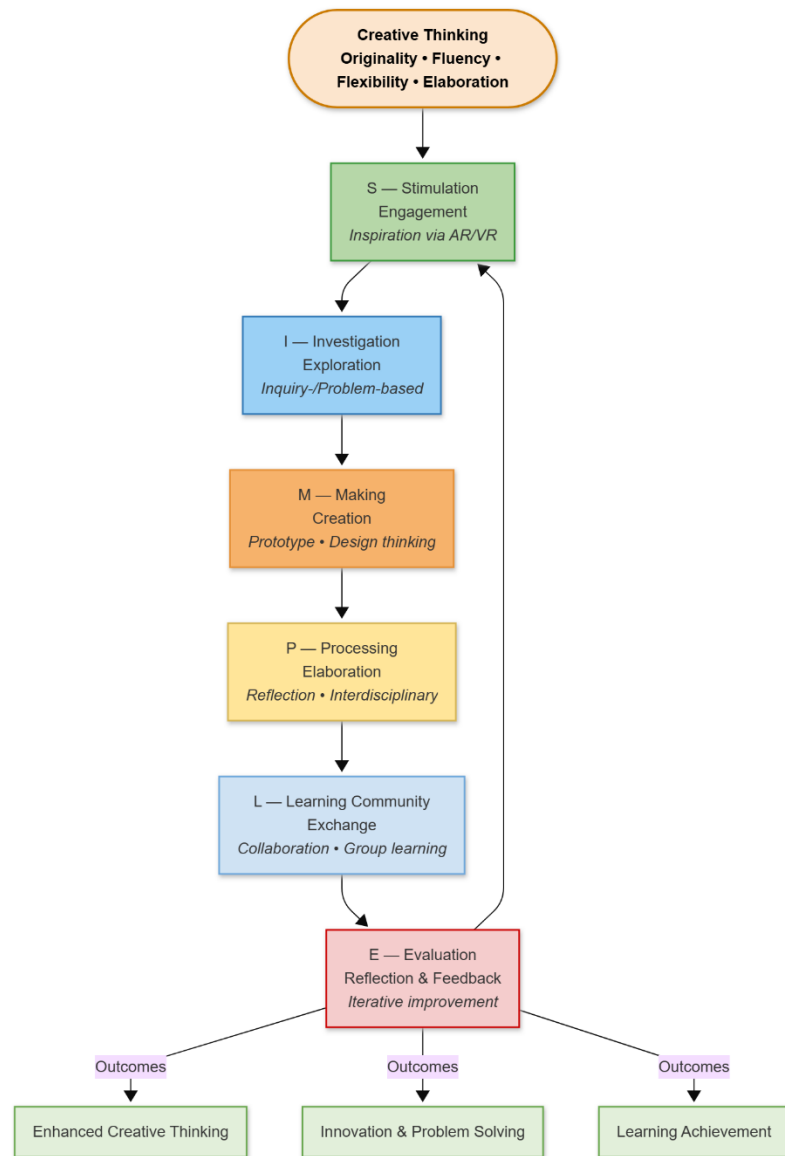


Figure 1A. The SIMPLE Model: An Integrated Framework for Immersive STEAM Micro-learning to Enhance Creative Thinking.

Appendix A presents the SIMPLE Model is a pedagogical framework designed to enhance learners' creative thinking through an iterative and experiential process. The model integrates six key phases: Stimulation, Investigation, Making, Processing, Learning Community, and Evaluation to create a dynamic, constructivist cycle that fosters creativity, innovation, and learning achievement.

Figure 1A illustrates the process, which begins with S (Stimulation), emphasizing learner engagement and emotional readiness through immersive experiences such as AR/VR environments. These experiences serve as catalysts for curiosity and motivation.

Next, I (Investigation) focus on exploration through inquiry- or problem-based learning, encouraging students to formulate questions, experiment, and collaboratively seek solutions.

The M (Making) phase focuses on creation and prototyping through design thinking, enabling learners to transform abstract ideas into tangible artifacts.

Subsequently, P (Processing) supports elaboration and reflection by integrating interdisciplinary knowledge, deepening conceptual understanding, and connecting diverse domains.

The L (Learning Community) stage emphasizes collaboration and knowledge exchange, with learners engaging in group discussions and peer learning, reinforcing the social dimension of creativity.

Finally, E (Evaluation) emphasizes reflection and feedback, enabling iterative improvement and metacognitive growth.

The model's cyclical flow underscores the interconnectivity between stages, illustrating how feedback loops continuously stimulate new ideas and refinements. Ultimately, the outcomes of this process enhance creative thinking, innovation, problem-solving, and learning achievement, representing the transformation of learners into adaptive, creative thinkers equipped for complex, technology-enhanced challenges.