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Effectiveness of AI-supported situated immersive virtual reality environment on learning motivation, flow experiences, and achievement in packaging structure design

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Abstract

This study examined the effectiveness of the Situated Immersive Virtual Reality (SIT-IVR) learning environment with AI-supported scaffolding on learning motivation, flow experience, and achievement among design students. A quasi-experimental design was employed in a study involving 80 third-year undergraduate students at a university in Shanghai, China. They were randomly assigned to an experimental group (N = 40) that used SIT-IVR and a control group (N = 40) that used desktop VR. The data were analysed using MANOVA, independent-samples t-tests, and ANOVA. The results showed that the experimental group's learning motivation and flow experience were significantly higher than those of the control group. The experimental group's achievement exceeded that of the control group (adjusted means: 77.96 vs 69.14, $p = 0.002$, partial $\eta^2 = 0.120$). The findings indicate that the SIT-IVR learning environment, based on situated instructional design, can enhance design students' learning. Its strengths do not stem from technology itself, but from the integration of authentic tasks, immersive interaction, and AI-supported scaffolding. Therefore, the SIT-IVR learning environment can serve as a model for developing intelligent immersive e-learning environments in design education.

Keywords: AI-supported scaffolding, Design education, Flow experience, Immersive virtual reality, Learning motivation, Situated learning.

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Contents

Contribution of this paper to the literature
This study makes an original contribution by integrating situated learning theory with AI-supported scaffolding within a situated immersive VR learning environment. It demonstrates that the effectiveness of SIT-IVR stems from the synergistic interaction of authentic tasks, spatial interaction, and intelligent support, rather than from technology alone. Furthermore, applying AI-supported situated immersive VR helps address an empirical gap in the development of intelligent immersive e-learning environments in design education.

1. Introduction

Immersive virtual reality (IVR) is gradually becoming a key technology for supporting authentic, interactive, and experiential learning in e-learning environments. It has been widely used in various learning settings as an instructional tool (Hamilton, McKechnie, Edgerton, & Wilson, 2021) and enables learning experiences that closely simulate real-world practice through immersive scenarios and interactions (Asad, Naz, Churi, & Tahanzadeh, 2021; Shirazi, Safavi, Aftabi, & Salimi, 2024). This feature is closely relevant to design education, as students often need to observe, manipulate, evaluate, and revise design concepts within real or simulated task contexts (Song, Zhang, Chang, Lu, & Zhang, 2019; Wang, Li, Jiang, & Feng, 2017).

In particular, packaging structure design presents a challenge because students require an understanding of complex spatial-structural relations and constantly shift their thinking between two-dimensional (2D) layouts and three-dimensional (3D) structures (Milovanovic & Gero, 2020; Sorby, 2000). However, immersion alone may not provide sufficient learning support. In complex design tasks, students also require guidance, feedback, and scaffolding. Such support helps them understand task goals, follow operational steps, and correct mistakes during learning activities. Without such support, students may lose sight of their learning goals or struggle to navigate their learning pathways in IVR environments (Albus & Seufert, 2022; Wen, Lu, & Ali, 2024). Studies show that artificial intelligence (AI) can offer prompts, feedback, and task guidance based on students' behaviors and progress (Laine, Lindqvist, Korhonen, & Hakkarainen, 2022; Lampropoulos, 2025; Shirazi et al., 2024; Tan, Hu, Yeo, & Cheong, 2025). This potential opens new opportunities for intelligent instructional support in virtual learning environments.

However, technology alone does not automatically translate into learning outcomes (Hu, Ding, & Li, 2023; Mayer, 2009). Previous research has shown that an immersive environment can improve learners' interest, sense of presence, and positive experiences (Makransky & Petersen, 2021; Meyer, Omdahl, & Makransky, 2019; Parong & Mayer, 2018). However, high immersion does not necessarily lead to better learning outcomes; students may have a high cognitive load (Ali, Ullah, & Khan, 2022), distractions, and other difficulties (Albus & Seufert, 2022). Therefore, the effectiveness of IVR depends on two factors: first, whether technology is embedded in an appropriate instructional design (Mayer, 2009; Parong & Mayer, 2018); second, whether it can support students' sustained engagement, knowledge construction, and transfer of learning (Herrington & Oliver, 2000; Petersen, Klingenberg, Mayer, & Makransky, 2020).

Virtual learning environments should be designed and developed based on learning theories. Situated learning theory emphasizes that knowledge is acquired through engagement in real-world tasks and practices within specific social and cultural contexts, rather than in isolation from its context (Lave & Wenger, 1991). Similarly, Cognitive apprenticeship holds that students should gradually master skills through observing expert demonstrations, engaging in practice, receiving guidance, and obtaining scaffolding support within real or simulated task contexts (Collins, Brown, & Newman, 1989). So, IVR is valuable because it can place students in task environments that allow them to observe, explore, and manipulate relevant elements (Dalgarno & Lee, 2010; Freina & Ott, 2015). When IVR is connected with authentic tasks and clear learning activities, it can support participatory learning and the "learning by doing" approach emphasized by situated learning theory (Dawley & Dede, 2014; Schott & Marshall, 2018).

Learning motivation and flow experience are key indicators of psychological engagement in immersive learning environments (dos Santos et al., 2018; Makransky & Petersen, 2021; Yang, Cheng, Lin, Huang, & Ren, 2019). Learning motivation reflects students' willingness to participate in and continue learning (Cook & Artino, 2016). Flow theory proposes that learners are more likely to experience flow when tasks provide clear goals, immediate feedback, and a balance between challenge and skill (Csikszentmihalyi, 1990). Thus, these psychological factors may help explain how instructional design influences students' engagement and learning outcomes in design education. In immersive learning environments, learning outcomes are affected by multiple factors, including motivation, emotional experiences, cognitive processing, and instructional support (Makransky & Petersen, 2021; Petersen et al., 2020).

Although IVR and AI have been used in education, their instructional mechanisms in design courses remain unclear. Three research gaps are identified. First, fewer studies have explained the effectiveness of immersive environments by integrating learning theory and instructional design (Huang, Roscoe, Johnson-Glenberg, & Craig, 2021). Second, the relationships among authentic tasks, scaffolding, and psychological experiences (e.g., motivation, self-regulation) remain underexamined (Parong & Mayer, 2018; Petersen et al., 2020). Third, there is limited empirical evidence on how AI-supported scaffolding, when combined with situated authentic tasks, influences learning motivation, flow experience, and achievement (Jiawei & Mokmin, 2023; Song et al., 2019). Therefore, combining immersive VR with AI-supported scaffolding may offer a new approach to developing innovative e-learning environments in design education.

To address these gaps, this study designed and developed a Situated Immersive Virtual Reality Learning Environment (SIT-IVR) grounded in situated learning theory, integrated it with AI-supported scaffolding, and applied it to the packaging structure design course. It integrates authentic packaging design tasks, immersive spatial interaction, and an AI-Supported Situated Expert Agent (AI-SEA). AI-SEA serves as an intelligent instructional support tool. It provides contextual prompts, process guidance, and immediate feedback based on the students' task progress and operational behavior. The purpose of this study is to investigate the effects of SIT-IVR on learning motivation, flow experience, and achievement by comparing it with a desktop VR learning environment.

2. Literature Review

2.1. Situated Immersive Virtual Reality in Design Education

Design education has practical, situated, and problem-oriented characteristics (Asojo & Vo, 2021; Milovanovic & Gero, 2020). While students need to understand design principles, they also need to cultivate design competence through continuous revision and reflection in specific task contexts (Hettithanthri & Hansen, 2022). In the packaging structure design course, students face the particular challenge of frequently shifting between 2D die-cut diagrams and 3D package structures (Song et al., 2019; Zhang, 2022), and evaluating the relationships among structural function, material selection, and visual presentation (Wang et al., 2017). This process of spatial translation is especially challenging for novice designers (Hsieh, Chen, & Chen, 2022; Moritz & Youn, 2022).

Textbooks, PowerPoint presentations, or desktop VR environments often struggle to support such spatial cognitive processes effectively. These tools can present images, animations, or basic 3D models. Still, they do not fully demonstrate how a 2D layout becomes a 3D structure through folding, interlocking, and gluing, which directly affect structural formation and function (Shan, Ma, Tang, & Chen, 2018; Zhang, 2022). Although students can view and interact with 3D objects in VR, the effectiveness of VR still depends on students' spatial ability, the depth of interaction, and the quality of instructional support (Lee & Wong, 2014; Moritz & Youn, 2022).

When procedural support is limited, students may focus on memorizing structural names and procedures, rather than developing an understanding of spatial depth, spatial-structural relations, and the logic of structural formation (Moritz & Youn, 2022). This challenge becomes even more severe when task complexity exceeds students' current abilities. They may experience a higher cognitive load (Johnsdorf et al., 2023) and find it difficult to maintain the challenge-skill balance required for flow experience (Csikszentmihalyi, 1990; Jackson, Martin, & Eklund, 2008), thereby diminishing their sustained engagement in learning (Wen et al., 2024).

To address these issues, this study designed and developed SIT-IVR for the packaging structure design course, based on situated learning theory and cognitive apprenticeship. SIT-IVR aims to provide students with a situated learning environment supported by instructional scaffolding.

2.2. Learning Motivation, Flow Experience, and Achievement in Immersive Learning Environments

The effectiveness of an immersive learning environment is often assessed in terms of three key factors: learning motivation, flow experience, and achievement. This is because learning outcomes in immersive environments are closely related to students' motivation, cognitive engagement, self-regulation, and emotional experiences (Makransky & Petersen, 2021; Petersen et al., 2020). Among these factors, learning motivation is an important psychological factor that promotes students' active engagement in learning tasks and sustains cognitive engagement (Cook & Artino, 2016; Svinicki & Vogler, 2012). In a VR learning environment, the learning process relies heavily on students' self-regulation and sustained engagement (Cook & Artino, 2016). Therefore, learning motivation not only affects students' willingness to participate in learning, but also influences their level of engagement and learning outcomes.

Flow experience is an optimal state characterized by high concentration, a sense of control, and intrinsic enjoyment during learning activities (Csikszentmihalyi, 1990). An increasing number of studies have used flow experience to examine users' acceptance of new technologies (Al-Emran & Granić, 2021; Gao & Bai, 2014). When task challenges are matched to individuals' skill levels and are accompanied by clear goals and immediate feedback, students are more likely to experience flow (Faiola, Newlon, Pfaff, & Smyslova, 2013; Jackson et al., 2008). When the challenge is too high, students are prone to frustration, whereas when it is too low, they are likely to become bored (Jackson & Csikszentmihalyi, 1999; Peng et al., 2025; Yin, Goh, & Hu, 2024). Therefore, in packaging structure design learning, flow experience not only reflects students' sense of control but also indicates their ability to maintain concentration and engage in continuous exploration during complex spatial tasks. Moreover, achievement is used to measure students' understanding and mastery of packaging structure design.

Therefore, SIT-IVR is designed as a learning environment featuring authentic packaging structure tasks, immersive interaction, and intelligent learning scaffolding. Authentic tasks help students connect learning goals with actual design problems; immersive interaction supports learners' sense of control and engagement in spatial operations; the AI-supported Situated Expert Agent (AI-SEA) enables learners to adjust their learning pathways, helping them stay focused on learning tasks. These characteristics support active participation, sustained engagement, clear goals, and immediate feedback associated with learning motivation and flow experience.

Based on the above explanation, this study uses a desktop VR learning environment as the control condition to evaluate the effects of SIT-IVR on learning motivation, flow experience, and achievement. The research hypotheses are set systematically as follows:

H_1: Compared with desktop VR, SIT-IVR significantly improves learners' motivation to learn.
H_2: Compared with desktop VR, SIT-IVR significantly improves learners' flow experience.
H_3: Compared with desktop VR, SIT-IVR significantly improves learners' achievement.

3. Methods

3.1. Research Design

This study utilized a quasi-experimental method to evaluate the effects of SIT-IVR on learners' learning motivation, flow experience, and achievement. The experimental group learned using SIT-IVR, whereas the control group learned using desktop VR. Learning motivation, flow experience, and achievement served as the dependent variables (DVs).

3.2. Participants

A total of 80 third-year Visual Communication Design students from Lida University in Shanghai, China, were recruited to participate in this study. None of them had previously studied packaging structure design. They participated voluntarily and had no prior experience with the learning systems used in this study. Participants were randomly allocated to two groups: the control group and the experimental group, with 40 learners in each group. The sample consisted of 35 male students and 45 female students, aged between 20 and 22 years.

All participants were from the same major and academic year, which helped reduce potential bias in the research results arising from differences in academic background and prior knowledge. Before the intervention, participants were informed of the study's aims, procedures, data use, and their rights. Informed consent was obtained from all participants. The entire research process followed ethical guidelines, and all collected data were used only for this study.

3.3. Learning Environments and Instructional Design

The learning content, tasks, and duration were the same for both groups. The learning content covers the structural names, forming characteristics, functional design, dimensional calculations, and visual element design of folding-carton structures.

Thus, the learning environment and its instructional support were the only major differences between the two groups.

3.3.1. SIT-IVR Learning Environment

SIT-IVR was designed based on situated learning theory and cognitive apprenticeship. It was developed using the Unity platform to enable immersive interaction through an HTC Vive head-mounted display (HMD) device and an HTC Vive Controller 2.0.

SIT-IVR was situated in a simulated Shanghai Chongming cake shop, incorporated authentic packaging structure design tasks involving Mid-Autumn Festival gift packaging for Chongming cakes, and used an AI-Supported Situated Expert Agent (AI-SEA) as an instructional scaffold. AI-SEA did not complete tasks for students, but provided situated prompts, operational guidance, and immediate feedback based on students' task progress and operational behaviors. In addition, SIT-IVR supported 360° viewing of packaging models, and students could use the controller to open, zoom, fold, and modify packaging components and design elements. Table 1 presents the detailed learning activities implemented in SIT-IVR.

Table 1. Learning Activities and Processes for Packaging Structure Design in SIT-IVR.

Activities	Process
Task introduction	1. Students enter the SIT-IVR, which is set in a Shanghai Chongming cake shop, and are tasked with designing a Mid-Autumn Festival gift package for Shanghai Chongming cakes. 2. Students review the learning objectives and requirements, including the structural characteristics of folding cartons, functional design, dimensional calculations, and visual elements.
Situated exploration	1. Students explore a case study of the current folding paper packaging for Chongming cakes in the context of a Chongming cake shop in Shanghai. 2. Understanding the relationship between structure, function, materials, and visual expression.
2D to 3D transformation	1. Through operations such as folding, rotating, and scaling, students explore the process of converting 2D die-cut diagrams into a 3D paper packaging structure, thereby gaining an understanding of the folding logic and dimensional relationships.
Immersive operation	2. Students begin manipulating die-cut diagrams, adjusting crease lines, glue joints, dust flaps, and locking mechanisms, while applying functional design and structural calculations to design gift packaging for the Mid-Autumn Festival.
AI-supported guidance	1. AI-SEA provides contextual prompts, step guidance, and immediate feedback (such as structural soundness, dimensional accuracy, and visual harmony) based on students' task progress and operational behavior.
Reflection and revision	1. Students review the design of the gift packaging, assess whether the structural design meets functional and visual requirements, and make revisions and improvements based on AI feedback.
Assessment	1. Students complete the learning task. 2. Students receive a comprehensive assessment of their understanding of packaging structure, 2D to 3D transformation ability, the reasonableness of functional and dimensional design, and the application of visual elements.

3.3.2. Desktop VR Learning Environment

The control group used a desktop VR learning environment. This environment displayed 3D scenes, packaging models, and learning content related to packaging structure design on a computer screen. Students could use a mouse and keyboard to view, rotate, zoom, and open the packaging models. Unlike SIT-IVR, the desktop VR environment did not use an HMD or incorporate AI-supported scaffolding. Consequently, it could not provide situated prompts and feedback based on the student's learning progress.

3.4. Instruments

Learning motivation was measured by the Instructional Materials Motivation Survey (IMMS). This survey is based on Keller (2010) ARCS model of motivation and assesses the effects of learning materials and learning environments on students' motivation. It consists of four components: Attention, Relevance, Confidence, and Satisfaction. IMMS has a total of 12 items and is suitable for technology-supported learning environments (Loorbach, Peters, Karreman, & Steehouder, 2015). The flow experience was measured using the Flow State Scale (FSS) developed by Pearce, Ainley, and Howard (2005). The scale measures the overall level of flow during learning activities. The FSS consists of 15 items across three dimensions of engagement, enjoyment, and perceived control.

Both the IMMS and the FSS use a five-point Likert scale, ranging from 1 ("strongly disagree") to 5 ("strongly agree"). The results of the reliability analysis showed that the Cronbach's α coefficients were 0.81 for the IMMS and 0.87 for the FSS.

Achievement was examined using the Packaging Structure Design test (PSD). The test consisted of 20 multiple-choice questions, each with one correct answer. The test covered folding-carton types, the functions of different components in 2D flat patterns, 3D formed structures, structural functions, and structural calculation methods. The PSD pretest was administered before the intervention, and the PSD posttest was administered after the intervention. The PSD pretest was used to assess students' prior knowledge in both groups, whereas the PSD posttest was used to measure students' achievement after the intervention.

All instruments used in the study were translated using a forward-backward translation approach to ensure linguistic accuracy and content equivalence. Specific wording was also appropriately adjusted to reflect the study context. Two experts in educational psychology evaluated the revised instruments to confirm their content validity.

3.5. Research Procedure

Before the intervention, 80 participants completed the PSD pretest on packaging structure design knowledge, which lasted 15 minutes. Then, the researcher explained the experimental process, learning tasks, and operational requirements to the participants. They were given a 5-minute practice session to reduce the impact of their unfamiliarity with the devices on the learning process.

During the intervention stage, the experimental group completed the same learning activities using SIT-IVR, whereas the control group completed the same activities using desktop VR. Using a Shanghai Chongming cake shop as the learning context and "Designing Mid-Autumn Festival Gift Packaging" as the task, both groups were required to complete learning activities such as identifying 2D flat patterns, understanding 3D package structures, assessing structural functions, and refining design proposals. The intervention lasted 35 minutes.

At the end of the intervention, all participants immediately completed the IMMS, FSS, and PSD posttests. The assessments took 25 minutes in total. The research procedures were identical for both groups. The entire procedure is shown in Figure 1.

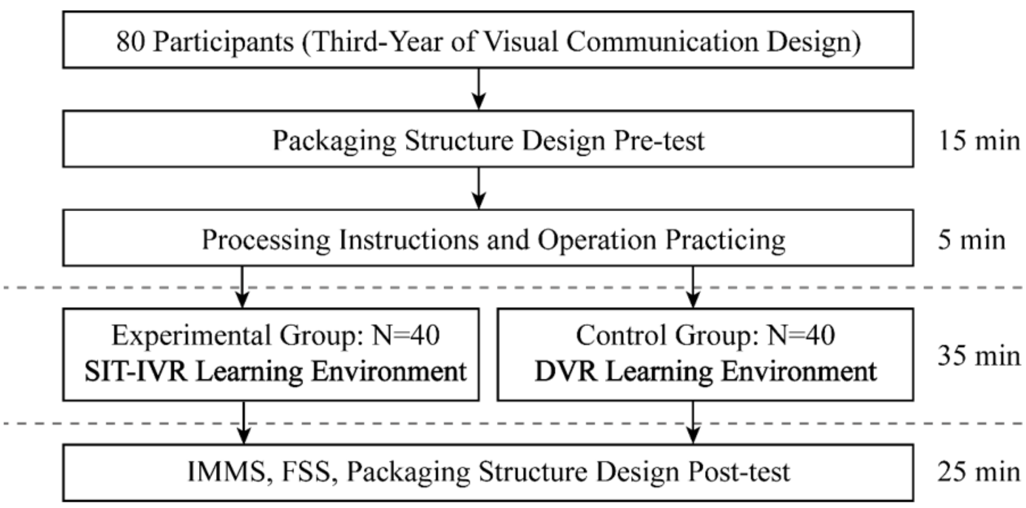

Figure 1. The research procedure conducted in this study.

3.6. Data Analysis

In this study, data were processed and analyzed using SPSS Statistics version 27. Descriptive statistics were used to summarize the participants' demographic information (e.g., age and gender) and the main study variables, including frequencies, means, and standard deviations.

Before the intervention, baseline equivalence between the two groups was examined. Independent-samples t-tests (t-tests) were performed to examine whether the experimental and control groups differed in age and PSD pretest scores measuring prior knowledge of packaging structure design. If the two groups did not differ significantly with respect to these variables ($p > 0.05$), they were considered comparable at baseline.

After the intervention, a multivariate analysis of variance (MANOVA) was conducted using learning motivation, flow experience, and achievement as the dependent variables to evaluate the overall effect of the learning environment on these learning outcomes. Subsequently, independent-samples t-tests were performed to compare the two groups with respect to learning motivation and flow experience.

To further examine the effect of the learning environment on achievement, an analysis of covariance (ANCOVA) was conducted. The type of learning environment was the independent variable (IV), the achievement posttest score was the dependent variable (DV), and the pretest score was the covariate. The purpose of conducting ANCOVA was to assess the effect of SIT-IVR on achievement while controlling for participants' pretest scores.

The significance level was set at $\alpha = 0.05$ for all statistical tests. In addition to p-values, effect sizes were reported to indicate the magnitude of the intervention effects. For MANOVA, Wilks' λ was used as the multivariate test statistic, together with partial η^2 as the effect size. Cohen's d was reported for independent-samples t-tests, and partial η^2 was reported for ANCOVA.

4. Results

4.1. Baseline Equivalence and Descriptive Statistics

To evaluate whether the experimental and control groups were comparable at baseline before the intervention, this study compared their age, gender distribution, and pretest scores for packaging structure design knowledge. The results presented in Table 2 indicated that the mean age of the experimental group was 20.83 (SD = 0.71), whereas that of the control group was 21.13 years (SD = 0.79). The age difference between the two groups was not statistically significant, $t(78) = 1.78$, $p = 0.078$, Cohen's $d = 0.40$. The gender distribution was similar between the two groups. The experimental group included 17 males and 23 females, while the control group included 18 males and 22 females; the chi-square test also indicated no significant difference between the groups, $\chi^2 = 0.05$, $p = 0.823$. The mean pretest score for the experimental group was 25.48 (SD = 6.80), while that for the control group was 24.60 (SD = 7.95); similarly, the difference was not statistically significant, $t(78) = 0.53$, $p = 0.60$, Cohen's $d = 0.12$. These results indicate that the two groups were comparable at baseline with respect to age, gender distribution, and prior knowledge.

Table 2. Baseline Equivalence Between the Experimental and Control Groups.

Source	Experimental group (N=40)	Control group (N=40)	Test statistic	p	Effect size
Age (M ± SD)	20.83 ± 0.71	21.13 ± 0.79	t = 1.78	0.078	Cohen's d = 0.40
Gender (Male/Female)	17 / 23	18 / 22	$\chi^2 = 0.05$	0.823	—
Pretest (M ± SD)	25.48 ± 6.80	24.60 ± 7.95	t = 0.53	0.598	Cohen's d = 0.12

4.2. Multivariate Effect of Learning Environment on Learning Outcomes

After the intervention, this study employed MANOVA to examine the overall effect of the type of learning environment on learning motivation, flow experience, and achievement. The type of learning environment served as the IV, while learning motivation, flow experience, and achievement served as the DVs.

The results presented in Table 3 showed that the type of learning environment had a significant multivariate effect on the three learning outcome variables, with Wilks' $\Lambda = 0.630$, $F(3, 76) = 14.884$, $p < 0.001$, and partial $\eta^2 = 0.370$. These findings indicated a significant overall difference between the experimental and control groups across the combined dependent variables. In other words, compared with desktop VR, SIT-IVR significantly enhanced learners' combined learning outcomes.

Table 3. MANOVA Results for Learning Motivation, Flow Experience, and Achievement.

Effect	Multivariate test	Value	F	df	Error df	p	Partial η^2
Learning environment	Wilks' Lambda	0.630	14.884	3	76	< 0.001	0.370

Note: Partial η^2 indicates the effect size. According to Cohen's conventional criteria, Partial η^2 values are interpreted as small (0.01), medium (0.06), and large (0.14).

4.3. Effect of Learning Environment on Learning Motivation

To examine whether learning motivation differed between the two learning environments, a t-test was used to assess whether the two groups differed in learning motivation scores. Table 4 presents the results, showing that learning motivation scores were significantly higher in the experimental group (M = 3.728, SD = 0.494) than in the control group (M = 3.173, SD = 0.546), $t(78) = 4.772$, $p < 0.001$, Cohen's $d = 1.07$. This result indicates that learners in the SIT-IVR group had significantly higher learning motivation than those in the desktop VR group. Therefore, H_1 was supported.

Table 4. Independent-Samples t-test Results for Learning Motivation.

Variable	Group	Mean	SD.	t	p	df	Cohen's d
Learning Motivation	Experimental Group (N=40)	3.728	0.494	4.772	<0.001	78	1.07
	Control Group (N=40)	3.173	0.546	4.772	<0.001	78	1.07

Note: SD refers to standard deviation; Sig. refers to the significance value; df refers to degrees of freedom. Effect magnitude was interpreted using Cohen's d, where values of 0.20, 0.50, and 0.80 correspond to small, moderate, and large effects, respectively.

4.4. Effect of Learning Environment on Flow Experience

To examine whether flow experience differed between the two learning environments, a t-test was conducted. The results in Table 5 indicate that flow experience scores were significantly higher in the experimental group (M = 3.553, SD = 0.472) than in the control group (M = 3.024, SD = 0.632), $t(78) = 4.242$, $p < 0.001$, Cohen's $d = 0.95$. This result indicates that learners in the SIT-IVR group reported significantly higher flow experience than those in the desktop VR group. Therefore, H_2 was supported.

Table 5. Independent-Samples t-test Results for Flow Experience.

Variable	Group	Mean	SD.	t	p	df	Cohen's d
Flow Experience	Experimental Group (N=40)	3.553	0.472	4.242	<0.001	78	0.95
	Control Group (N=40)	3.024	0.632	4.242	<0.001	78	0.95

Note: SD refers to standard deviation; Sig. refers to the significance value; df refers to degrees of freedom. Effect magnitude was interpreted using Cohen's d, where values of 0.20, 0.50, and 0.80 correspond to small, moderate, and large effects, respectively.

4.5. Effect of Learning Environment on Achievement

To determine whether the type of learning environment affected achievement, an ANCOVA was conducted. The type of learning environment served as the IV and had two levels: SIT-IVR and desktop VR. The achievement posttest score served as the DV, while the pretest score served as the covariate to control for differences in learners' prior knowledge.

After controlling for pretest scores, Table 6 indicated that achievement was significantly affected by the type of learning environment, $F(1, 77) = 10.509$, $p = 0.002$, partial $\eta^2 = 0.120$. The adjusted mean achievement scores were higher in the experimental group (77.96, SE = 2.49) than in the control group (69.14, SE = 2.49), indicating a medium effect. This finding indicates that SIT-IVR was more effective than desktop VR in supporting learners' understanding and application of packaging structure design knowledge. Therefore, H_3 was supported.

Table 6. ANCOVA Results for Achievement.

Source	df	F	p	Partial η²
Pretest	1	3.979	0.050	0.049
Group	1	10.509	0.002	0.120

Note: Adjusted means are reported for the achievement posttest. Partial η² values are interpreted as small (0.01), medium (0.06), and large (0.14).

The above findings indicate that the two groups were comparable at baseline with respect to age, gender distribution, and prior knowledge. After the intervention, the MANOVA results demonstrated a significant multivariate effect of the type of learning environment on the combined dependent variables of learning motivation, flow experience, and achievement. Further analyses indicated that, compared with desktop VR, learners in the SIT-IVR group reported significantly higher learning motivation and flow experience and achieved significantly higher posttest scores after controlling for pretest scores, supporting H_1, H_2, and H_3. In summary, SIT-IVR was associated with more positive psychological learning experiences and better achievement in packaging structure design.

5. Discussion and Conclusion

The present study used a quasi-experimental design to evaluate the effectiveness of a Situated Immersive Virtual Reality learning environment (SIT-IVR) in a packaging structure design course. The study findings indicate that, compared with the desktop VR learning environment, SIT-IVR had significant advantages in the combined learning outcomes and was associated with higher learning motivation and flow experience, as well as greater achievement. The following discussion examines the mechanisms underlying SIT-IVR from the perspectives of the three outcome variables and further explains how IVR and AI can be developed and integrated into an effective learning environment through the guidance of learning theory and instructional design.

From the perspective of learning motivation, the higher motivation observed in the SIT-IVR group may be attributable to authentic task contexts, immersive interaction, and AI-supported scaffolding. According to Self-Determination Theory (SDT), a learning environment that supports learners' autonomy, competence, and relatedness is likely to promote their intrinsic motivation (Deci & Ryan, 2000). In this study, the authentic task contexts embedded in SIT-IVR helped learners understand the relationship between design knowledge and practical problems, thereby enhancing the contextual meaning and relevance of the learning activities (Herrington & Oliver, 2000). Meanwhile, immersive interaction may have enhanced learners' sense of competence and self-efficacy through a sense of presence and control (Makransky & Petersen, 2021). In addition, the prompts and feedback provided by the AI-supported Situated Expert Agent (AI-SEA) may have supported learners in autonomously adjusting their task pathways, while AI-supported scaffolding may have addressed their need for autonomy (Collins et al., 1989; Laine et al., 2022; Lampropoulos, 2025). Consequently, SIT-IVR may have supported learners' needs for autonomy and competence, thereby contributing to higher learning motivation.

The higher flow experience observed in the SIT-IVR group may be explained by the combined effects of authentic tasks, immersive interaction, and scaffolding. Csikszentmihalyi (1990) Flow Theory points out that clear goals, immediate feedback, and a balance between challenge and skill are important conditions for experiencing flow. In this study, the authentic packaging structure task provided clear goals and problem contexts. At the same time, immersive interaction enabled learners to directly observe, rotate, fold, and modify packaging structures, thereby enhancing their sense of presence and engagement. Previous studies have indicated that presence is strongly associated with flow experience (Cummings & Bailenson, 2016; Faiola et al., 2013). AI-SEA provided prompts and immediate feedback. This support helped learners evaluate the appropriateness of their operations and adjust their learning pathways, which may have reduced goal disorientation (Wen et al., 2024). It may also have helped learners maintain a balance between task challenges and the skills required for flow. It is worth noting that the learning outcomes associated with IVR are not determined by immersion alone (dos Santos et al., 2018), but depend on its integration with appropriate task design and learning support (Keller, Walker, Amenduni, Tela, & Cattaneo, 2025; Petersen et al., 2020). Therefore, the higher flow experience associated with SIT-IVR may not have resulted automatically from immersive technology but from the combined influence of these three instructional design factors.

In terms of achievement, the higher achievement observed in the SIT-IVR group suggests that a situated immersive learning environment can make packaging structure knowledge more intuitive (Dalgarno & Lee, 2010) and accessible through operational learning experiences (Matovu et al., 2023). This benefit was particularly evident in helping students understand the spatial transformation from 2D die-cut diagrams into 3D carton structures, which is one of the primary challenges in packaging structure design (Shan et al., 2018; Zhang, 2022). Studies have pointed out that transformation from 2D forms into 3D structures is an important spatial cognitive ability in design learning (Hsieh et al., 2022). In this study, SIT-IVR enabled students to directly experience and understand the logic of structural formation through operations such as rotation, folding, zooming, and modification. However, a 3D environment alone does not guarantee effective learning; the effects of VR are influenced by instructional design and feedback mechanisms (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014). By linking spatial operational experiences with structural principles, functional requirements, and visual design, AI-SEA may have helped students transform spatial operations into comprehensible and applicable design knowledge, thereby contributing to their higher achievement.

In conclusion, this study addresses the limited explanation in previous studies of the mechanisms underlying the effectiveness of immersive learning environments. Previous studies have largely focused on variables such as immersion, presence, or academic performance (Akgün & Atici, 2022; Johnson-Glenberg, 2018), while explanations of how technology affects learning outcomes through learning theory and instructional design remain relatively scarce. MANOVA results indicated that the type of learning environment had a significant multivariate effect on the combined dependent variables of learning motivation, flow experience, and achievement, suggesting that its effects should be considered across multiple learning outcomes rather than through a single outcome alone. These findings do not imply that IVR or AI technologies, by themselves, automatically improve learning outcomes (Hu et al., 2023; Huang et al., 2021; Mayer, 2009). Prior studies have confirmed that the efficacy of immersive technologies depends on cognitive processing, task design, and instructional support (Parong & Mayer, 2018).

Consequently, the effectiveness of SIT-IVR may stem from the integration of situated learning theory and cognitive apprenticeship principles within its instructional design. The authentic tasks were grounded in situated learning theory, while AI-SEA was designed according to cognitive apprenticeship principles. These findings provide empirical support for the proposition that AI-supported scaffolding and authentic tasks may work together to support learning motivation, flow experience, and achievement. Thus, the key to effective immersive learning environments lies not in the technology itself but in whether the technology is embedded in theory-guided instructional design and integrated with authentic learning tasks and scaffolding.

6. Implications, Limitations, and Future Research

The present study provides practical insights and guidance for developing e-learning environments in design education. IVR and AI technologies should not be used merely as tools for creating immersion. Their pedagogical value depends on whether they support clear goals, authentic tasks, and procedural scaffolding. In complex tasks such as packaging structure design, instructional design needs to maintain a balance between independent exploration and scaffolding support.

This study also has certain limitations. First, this study used a short-term quasi-experimental design. It examined only immediate effects, without assessing long-term retention, knowledge transfer, or the development of design competencies. In the future, multiple rounds of learning tasks could be used to examine the effects of SIT-IVR on long-term learning outcomes. Second, this study did not compare the effects of different AI-supported scaffolding strategies. Future studies could further investigate how feedback types, intervention timing, scaffolding intensity, and the adaptability of scaffolding influence learning outcomes.

In summary, future intelligent immersive learning environments should place greater emphasis on integrating instructional design, authentic tasks, scaffolding, and learners' psychological experiences, thereby ensuring that technology truly serves the learning process.

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