

Article

Enhancing Design Creativity Through Embodied Platforms: An Exploratory Study Comparing Desktop, Mixed Reality, and Virtual Reality in Design Education

Wenjuan Wang ^{1,†}, Zhaolin Lu ^{1,†} , Siqi Yu ¹ , Haonan Yao ^{2,3} , Fuqi Xie ² , Lingyun Yu ² and Yue Zhang ^{4,*}

¹ School of Design & Arts, Beijing Institute of Technology, Beijing 102401, China;

wenjuan.wang@bit.edu.cn (W.W.); zhaolin.lu@bit.edu.cn (Z.L.); 3120241937@bit.edu.cn (S.Y.)

² School of Advanced Technology, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China;

haonan.yao@nottingham.edu.cn (H.Y.); fuqi.xie20@student.xjtlu.edu.cn (F.X.); lingyun.yu@xjtlu.edu.cn (L.Y.)

³ School of Computer Science, University of Nottingham Ningbo China, Ningbo 315100, China

⁴ College of Architecture and Art, Hefei University of Technology, Hefei 230001, China

* Correspondence: zhangyue@hfut.edu.cn

† These authors contributed equally to this work.

Highlights

Please indicate how your work links to systems science via your contributions to systems practice, theory, and/or methodology.

- This study extends embodied cognition theory to design education by conceptualizing design platforms as systems with different levels of embodiment, in which bodily interaction and spatial context jointly shape creative activities.
- Methodologically, the study combines Consensual Assessment Technique (CAT) with Lag Sequential Analysis (LSA) to examine creative outcomes and design behavioral patterns across desktop, Mixed Reality (MR), and Virtual Reality (VR) platforms with different levels of embodiment.

What are the main findings and/or the implications of the main findings?

- The exploratory findings suggest that higher levels of embodiment were associated with higher creativity scores and more frequent and interconnected behavioral transitions, particularly in the highly embodied VR environment.
- Action-based metaphors and contextual consistency are proposed as potential explanatory factors, offering preliminary implications for the design of embodied learning platforms and creativity-oriented design education.

Abstract

Design education places strong emphasis on fostering students' creativity, and the rapid development of embodied immersive technologies presents new opportunities in this regard. This exploratory study recruits 34 university students with different levels of expertise (17 novices and 17 experienced learners). Each participant completes a 3D conceptual design task using three design platforms with varying levels of embodiment: desktop, Mixed Reality (MR), and Virtual Reality (VR). Data on self-reported sense of embodiment, design creativity, and behavioral patterns are collected and analyzed. The results suggest that the VR platform, which provides the highest level of embodiment, is associated with significantly higher overall creativity as well as six creativity dimensions: fluency, flexibility, elaboration, originality, aesthetics, and requirement fulfillment. In addition, students using the VR platform exhibit more frequent and interconnected transitions between design



Academic Editors: Magesh Chandramouli and Jose Sanchez

Received: 31 May 2026

Revised: 28 July 2026

Accepted: 14 August 2026

Published: 18 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

behaviors, suggesting more exploratory and flexible design processes. No significant interaction is observed between design platform and expertise level in the present sample, suggesting that the effects of platform embodiment are broadly similar for novice and experienced learners. Based on these findings, this study proposes action-based metaphor and contextual consistency as potential explanatory factors that may contribute to creativity enhancement in highly embodied design platforms. Practical implications are discussed from the perspectives of platform design, learner differences, and pedagogical strategies. Overall, this exploratory study provides preliminary empirical evidence for understanding how embodied design platforms may support creativity in immersive design education and offers a foundation for future research.

Keywords: design creativity; embodied platforms; immersive technology; behavioral pattern; design education

1. Introduction

Creativity is commonly defined as the ability to generate ideas that are both original and effective [1]. In design education at the university level, in addition to the teaching of relevant theories and technical skills, fostering students' creativity has become a central instructional objective. However, current digital design education still relies on traditional desktop-based CAD tools and teacher-centered instructional approaches, where knowledge is primarily delivered by instructors and passively received by students. This approach may, to some extent, limit students' intuitive understanding and hands-on interaction with 3D design objects and may constrain the development of creativity.

In recent years, immersive technologies such as Virtual Reality (VR) and Mixed Reality (MR) have introduced new possibilities for design education. Compared with traditional desktop-based systems, immersive platforms allow learners to directly manipulate design objects in 3D space and interact with virtual environments in real time. These technologies have been rapidly adopted in educational contexts, and existing studies suggest that they positively influence multiple aspects of learning, including student engagement [2], learning efficiency [3], and learning outcomes [4]. From a theoretical perspective, the educational benefits of immersive technologies can be understood through embodied cognition. This theory emphasizes that cognition is not confined to abstract mental representations but emerges from the dynamic interaction among the brain, body, and environment [5]. Prior research has suggested that embodied metaphors based on gestures or bodily actions can effectively facilitate learners' understanding and transfer of knowledge, yielding positive outcomes across diverse learning contexts [6,7]. Johnson-Glenberg [8] further proposed a taxonomy of embodiment in learning environments, highlighting three dimensions: the degree of sensori-motor engagement, the congruence between gestures and learning content, and the level of immersion experienced by users. It provides an important basis for analyzing embodied learning platforms across technological contexts.

In design education, immersive technologies are particularly valuable for disciplines involving complex 3D forms, such as product and industrial design. Previous research indicates that traditional 2D displays and mouse-keyboard interactions may hinder design thinking [9], whereas immersive platforms can support direct manipulation of 3D objects and real-time spatial perception during the design process [10]. However, several limitations remain in the literature. First, most studies focus on single VR or MR system, with limited comparisons across platforms with different levels of embodiment. Second,

existing research has primarily examined creative solutions while paying less attention to behavioral patterns during design activities, which may limit understanding of the mechanisms underlying creativity. Third, research on how learners with different levels of expertise respond to immersive design platforms remains limited.

To address these gaps, this exploratory study investigates the creative performance and design behavioral patterns of novice and experienced learners across three design platforms with different levels of embodiment: desktop, MR, and VR. Specifically, the following research questions (RQs) are proposed:

RQ1: Do design platforms with different levels of embodiment lead to differences in students' creativity? If so, what are the key influencing factors?

RQ2: How do design platforms with different levels of embodiment affect students' design behavioral patterns?

RQ3: Do students with different levels of expertise differ in their creative performance and design behaviors across platforms with different levels of embodiment?

RQ4: Based on the findings, what practical implications can be drawn for the development of embodied design platforms in future design education?

2. Literature Review

2.1. Creativity in Design and Its Assessment

With advances in technology and social development, increasing attention has been devoted to fostering students' creativity in education. In the context of design education, creativity is not only reflected in the generation of innovative ideas but also involves cognitive processes embedded in complex activities such as problem definition, solution exploration, and iterative refinement [11]. This highlights the dynamic and process-oriented nature of design creativity.

Various methods have been developed to assess creativity. Outcome-based evaluation is among the most widely used approaches. The Consensual Assessment Technique (CAT) evaluates creativity based on the assumption that experts within the same domain tend to reach a general consensus when judging the same work [12,13]. This method has been widely applied in design and educational research [14,15]. In addition, the Torrance Tests of Creative Thinking (TTCT) evaluates creativity using indicators such as fluency, flexibility, originality, and elaboration [16,17]. Beyond outcome-oriented approaches, process-oriented methods such as think aloud protocol analysis and behavioral analysis have been used to examine cognitive and behavioral patterns during creative tasks [18–20]. Combining outcome- and process-based approaches may therefore provide a more comprehensive framework for understanding creativity. However, relatively limited research has integrated these assessment approaches with emerging immersive technological environments. The present study combines CAT and behavioral analysis to comprehensively evaluate students' creativity in design tasks and further explores how different design platforms affect both creative performance and design processes.

2.2. Immersive Technologies in Design Education

With the growing adoption of digital technologies in education, immersive technologies such as VR and MR have become increasingly important. Compared with traditional 2D interfaces, immersive technologies can create more realistic learning environments. Recent research suggests that immersion should not be considered solely as visual realism but as a multidimensional experience involving perceptual, cognitive, and embodied dimensions [21]. Existing research has demonstrated that the rich perceptual experiences acquired through learners' bodily interactions with immersive environments facilitate the formation and development of cognitive processes during learning [22,23].

In design-related disciplines such as product, industrial, and architectural design, immersive technologies have also shown considerable potential. Immersive platforms create simulated environments in which users are situated within virtual spaces through head-mounted displays (HMDs) and can interact with the environment using controllers or bodily movements [24]. Consequently, within this digital environment, users can interact beyond some of the physical constraints associated with conventional desktop environments, allowing greater freedom in imagination and creative expression. Previous studies have reported positive effects of immersive platforms on creativity in design education. For example, Tang et al. reported that MR improved students' geometric analysis ability and creativity in product design courses [25]. Guan et al. further found that students using VR-based collaborative painting demonstrated better collaboration levels and higher creative quality of their works [26]. Similarly, Obeid and Demirkan demonstrated that immersive VR environments had a significant influence on flow and motivation, and consequently on design process creativity [10].

Despite these advances, existing research has primarily focused on single immersive technologies, with limited systematic comparisons across platforms with different levels of embodiment. Moreover, prior studies have largely emphasized design outcomes while paying relatively less attention to the creative process and the mechanisms underlying creative performance.

2.3. Embodied Cognition as a Theoretical Basis for Immersive Technologies

Embodied cognition theory challenges the traditional view in cognitive science that confines cognition to information processing within the brain, emphasizing that cognition arises from the dynamic interactions among the body, brain, and environment [27]. Recent reviews further highlight that embodied cognition includes multiple theoretical perspectives, such as grounded, enactive, and extended cognition, which emphasize the role of sensorimotor experiences and environmental interaction in shaping cognition [28]. The extended cognition perspective further proposes that cognition can extend beyond the brain through functional coupling with external objects and environmental resources [29,30]. From this perspective, immersive technologies such as VR and MR may function as cognitive extensions by integrating bodily actions, digital objects, and spatial contexts into a continuous interaction system. Perceptual and motor systems not only participate in cognitive processes but also constitute a fundamental basis of cognition. Embodied cognition has thus become increasingly influential in human–computer interaction research and provides important theoretical support for technologies such as wearable devices [31] and industrial robots [32].

The interactive and immersive characteristics of immersive technologies have drawn increasing attention to users' sense of embodiment in recent years [33]. Through virtual avatars and bodily interaction, users may develop a sense of body ownership and agency, referred to as embodiment [34,35]. Related research has mainly developed along two directions. First, researchers have focused on enhancing embodiment experience through technological advancements. For example, avatar appearance, wearable devices, and haptic controllers have been shown to influence users' sense of embodiment in VR environments [36,37]. Second, researchers have examined the cognitive and affective effects of embodied immersive technologies. Prior findings suggest that higher levels of embodiment can enhance motivation, usability, focus and flow in educational contexts [38,39]. However, existing research has largely focused on general cognitive or learning outcomes, with limited attention to how embodied experiences influence creative thinking processes, particularly in complex contexts such as design tasks. Drawing on embodied cognition theory,

this study therefore aims to investigate how different embodied immersive platforms affect design creativity and to explore the behavioral mechanisms that may underlie these effects.

3. Design and Development of an Immersive Design Platform

3.1. System Framework

This study, guided by embodied cognition theory, developed an immersive design platform that supports both VR and MR. The system framework of the platform is shown in Figure 1. The platform leverages the advantages of these technologies to enhance students' creativity in 3D design activities. Specifically, on the one hand, the system supports natural bodily interactions for users. The interaction logic of the system is consistent with users' bodily experiences in real-world creative activities, such as building blocks or shaping clay, which involve actions like moving, rotating, and scaling objects. In this system, students can rely on their prior embodied experiences to manipulate virtual objects directly and naturally using both hands and bodily movement. On the other hand, the system provides immersive design contexts. In VR mode, the system can flexibly adjust the environmental model according to the requirements of the design task, ensuring consistency between the design object and the virtual context. For example, when students are asked to design a sofa for a living room, they are placed within a virtual living room environment. In MR mode, the system directly displays the real-world environment, while allowing participants to view the environmental model from a bird's-eye perspective.

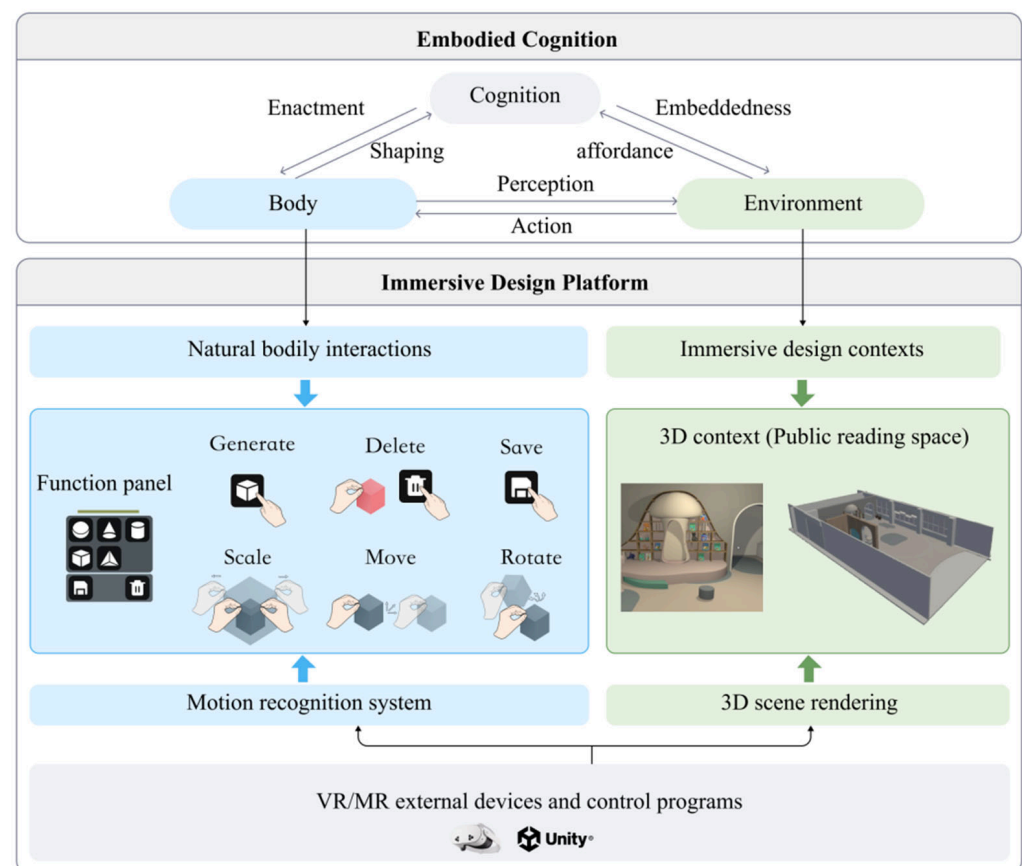


Figure 1. System Framework of the Immersive Design Platform.

3.2. Device Support

The experiment employs a head-mounted display, the Meta Quest 3S (Meta Platforms, Inc., Menlo Park, CA, USA), as shown in Figure 2. The device is lightweight and equipped with an adjustable elastic strap, allowing it to be adapted to different head sizes for extended and comfortable use. It supports a refresh rate of up to 120 Hz, ensuring clear and smooth visual performance. In addition, the device enables seamless switching between VR and MR modes. In MR mode, the built-in color passthrough cameras integrate the real-world environment into the virtual scene. This capability provides reliable hardware support for comparing design platforms with varying levels of embodiment in experimental settings.

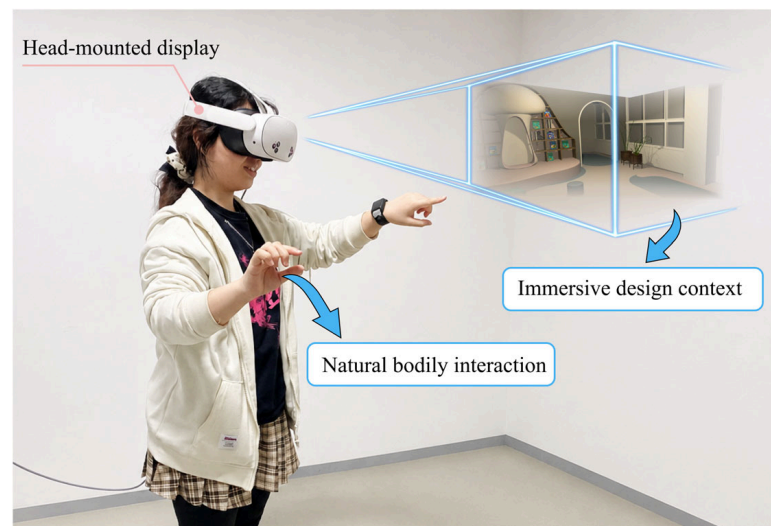


Figure 2. Experimental Scenario.

4. Method

4.1. Participants

Thirty-four undergraduate and master's students (19–28 years old, 17 females and 17 males) were recruited from a university in Beijing. Among them, 17 participants with formal education in design were classified as experienced learners, with majors including industrial design, product design, and graphic design. The remaining 17 participants without such training were classified as novice learners, with academic backgrounds in fields such as computer science, materials engineering, and law. A post hoc power analysis was conducted using G*Power 3.1 for the repeated-measures ANOVA. Assuming a significance level of $\alpha = 0.05$ and a medium effect size ($f = 0.25$), the achieved statistical power for the final sample of 34 participants was 0.89, exceeding the recommended threshold of 0.80. This result indicated that the sample size was adequate for the statistical analyses performed in this study.

4.2. Research Design

To compare the effects of design platforms with varying levels of embodiment on student creativity, three design platforms were established: desktop, MR, and VR. Based on the taxonomy of embodiment for educational platforms proposed by [8], the platforms were classified into low, medium, and high levels of embodiment, as shown in Figure 3. This framework is based on three factors: (a) the degree of sensori-motor engagement; (b) the congruence between gestures and the learning content; and (c) the level of immersion experienced by the user. To control for other potential confounding variables, the interaction interfaces, learning strategies, and experimental procedures were kept consistent across conditions.

Design Platforms	Desktop	MR	VR
			
Levels of Embodiment	Low	Medium	High
• Sensori-motor Engagement	Low	High	High
• Gestural Congruence	Low	High	High
• Immersion experience	Low	Medium	High

Figure 3. Comparison of embodiment levels across design platforms.

In this study, all participants completed 3D product conceptual design tasks across the three platforms. The entire experiment lasted approximately 60 min. To minimize potential order, learning, and fatigue effects, the presentation order of the desktop, MR, and VR conditions was counterbalanced across participants, with participants randomly assigned to different condition sequences. With informed consent, all experimental tasks were recorded in video and written formats for subsequent analysis. The experiment was conducted in a laboratory equipped with desktop computers and head-mounted devices under controlled lighting and a noise conditions.

4.3. Design Task

In this design task, participants were instructed to create conceptual 3D seating models using specified basic geometric shapes by combining and stacking them. The design solutions were required to align with the style of a specified public reading space (as shown in Figure 1), while balancing functionality and aesthetics. Five basic geometric shapes were provided in the experiment: cube, sphere, cylinder, cone, and triangular pyramid. Participants were allowed to perform six fundamental interaction operations, including generating, scaling, moving, rotating, deleting, and saving. Each task lasted 10 min, and participants were encouraged to produce as many design solutions as possible within the time limit.

4.4. Procedure

The overall procedure of this study was structured based on the 5E instructional model and was appropriately adapted to the characteristics of 3D design practice. The 5E model consists of five phases: engagement, exploration, explanation, elaboration, and evaluation. It was originally proposed by the Biological Sciences Curriculum Study (BSCS) [40] and emphasizes active knowledge construction through a progressive learning stages. In this study, the 5E framework was employed to ensure a consistent and comparable learning and design process across different design platforms. The procedure consisted of the following five phases.

(1) Engagement: The experimenters introduced the task background and explained how to use the desktop, MR, and VR platforms. All participants received standardized training on the three platforms before the formal task. The training was followed by a basic practice task, and participants proceeded to the formal experiment only after successfully completing the practice task. This procedure helped participants become familiar with the systems and ensured a comparable level of basic operational proficiency across platforms. (2) Exploration: Participants independently completed the 3D seating design task on different platforms with minimal intervention. This phase served as the core stage for idea generation. (3) Explanation: Conducted concurrently with the exploration phase, participants were asked to verbalize their design thinking and explain the concepts and structural features of their work. Meanwhile, the experimenter provided appropriate feedback to encourage reflection on their cognitive processes. (4) Elaboration: Participants reflected on and compare their interaction experiences and design processes across different platforms, and were encouraged to transfer these experiences to broader design contexts. (5) Evaluation: Domain experts assessed participants' creativity based on their design solutions, enabling a comprehensive evaluation of the effects of different design platforms on creativity.

4.5. Instruments

4.5.1. Assessment of Sense of Embodiment

Based on the embodiment taxonomy in educational contexts (see Section 4.2), the three design platforms (desktop, MR, and VR) were categorized into low, medium, and high levels of embodiment. To verify the intended differences in embodiment across the three platforms, participants' subjective sense of embodiment was measured using standardized questionnaires. In educational and immersive technology research, presence and agency are widely regarded as two key dimensions for evaluating the sense of embodiment [8,34,35]. Presence is commonly defined as a form of place illusion [41], or the subjective sense of "being there" in a virtual environment [42]. In this study, presence referred to participants' perceived immersion in a virtual design space. Even in desktop-based interaction, where the body is not represented through a virtual avatar, presence can still serve as a useful construct for explaining the relationship between the self and the virtual environment. The sense of agency is defined as the sense of having "global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will" [43]. In this study, agency referred to the extent to which designers perceive control over digital content during the design process. Based on existing embodiment questionnaires [44–46], the present study adapted questionnaire items related to presence and agency to assess participants' embodiment experiences. Reliability and validity analyses indicated high internal consistency (Cronbach's $\alpha = 0.928$) and good construct validity (KMO = 0.826, $p < 0.001$), suggesting that the questionnaire demonstrated good reliability and construct validity. The questionnaire items are listed in Table 1, and all items were rated on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree).

Table 1. Sense of Embodiment Questionnaire.

Dimension	Questionnaire Item
Sense of agency	I felt that my bodily movements occurred within the scene displayed.
	I felt that I could create naturally using this platform.
Sense of presence	I felt that my body was physically present in the scene displayed.
	I felt that I could almost touch the scene and design objects.

4.5.2. Consensual Assessment Technique

The Consensual Assessment Technique (CAT), proposed by Amabile [12], evaluates creativity based on the degree of agreement among experts within the same domain when judging creative works. CAT is particularly suitable for product-oriented creativity assessment in fields such as design and the arts [47]. In selecting evaluation indicators, this study referred to Guilford's four classic dimensions of creativity: fluency, flexibility, elaboration, and originality [48]. Based on this framework, Casakin and Kreitler [49] further extended the evaluation dimensions in design problem-solving to include usefulness, aesthetic representation, and requirement fulfillment. Similarly, Christensen and Ball [50] emphasized originality, functionality, and aesthetics as three core dimensions in expert evaluations of creativity within the field of design. Drawing on these established frameworks and considering the characteristics of the experimental task, the present study identified seven dimensions to evaluate the creativity of design solutions: fluency, flexibility, elaboration, originality, aesthetics, functionality, and requirement fulfillment. Each dimension was rated using a seven-point Likert scale. Four experts with professional experience in industrial design were invited to evaluate the creativity of the design solutions. Before evaluation, the experts were informed of the definitions of the seven creativity dimensions and the corresponding scoring criteria. They then independently rated all participants' solutions without discussion, and the final creativity score was calculated as the average rating across the four experts. The participants were anonymized, and the experts were blinded to the corresponding design platforms and participants' expertise levels. The inter-rater consistency was assessed using Cronbach's α and the intraclass correlation coefficient (ICC). The results showed a high level of agreement among the experts (Cronbach's $\alpha = 0.876$, ICC = 0.858), supporting the reliability of the consensual assessment.

4.5.3. Lag Sequential Analysis

Lag Sequential Analysis (LSA) was employed to examine participants' design behavior sequences. The primary purpose of LSA is to test the probability and statistical significance of specific behavioral sequences [51]. It is particularly suitable for identifying behavioral pathways and examining transition patterns within time-series data.

In this study, students' design behaviors were coded from video recordings and analyzed using LSA. Behavioral transition pathways were then identified, enabling analysis of students' design behavioral patterns across different design platforms. Based on existing coding schemes for creative design behavior [20], participants' behaviors were categorized into two main types: operational and observational behaviors, including eight specific design behaviors. Detailed coding definitions are provided in Table 2. Non-design-related actions, such as adjusting the head-mounted device, were excluded from the coding. To establish coding reliability, two researchers independently coded videos from two randomly selected participants. Inter-rater agreement was quantified using Cohen's kappa ($k = 0.85$), indicating a high level of consistency between the two coders.

Table 2. Behavioral Coding Scheme and Definitions.

Behavior		Code	Behavioral Definition	
			Desktop	MR/VR
Operational Behaviors	Generate	A1	Click the target object using the mouse	Tap the target object on the function panel with a finger
	Move	A2	Click the "Move" icon and drag the mouse along the X/Y/Z axis	Grasp the target object with one hand and move it directly

Table 2. Cont.

Behavior		Code	Behavioral Definition	
			Desktop	MR/VR
Operational Behaviors	Rotate	A3	Click the “Rotate” icon and drag the mouse along the X/Y/Z axis	Grasp the target object with one hand and rotate it directly
	Scale	A4	Click the “Scale” icon and drag the mouse along the X/Y/Z axis	Pinch the target object with both hands and move hands closer together or farther apart
	Delete	A5	Click the “Delete” icon	Grasp the target object with one hand and tap the “Delete” icon with the other hand
	Save	A6	Click the “Save” icon	Tap the “Save” icon with a finger
Observational Behaviors	Observe Environment	B1	Rotating the view around the environment center	Fixate gaze on the environment model for more than 2 s
	Observe Solutions	B2	Zooming in/out in top, right, and front views, or rotating the view around the solution center in perspective view.	Fixate gaze on the design solution for more than 2 s

5. Data Analysis

IBM SPSS Statistics Version 28 was used to conduct a 2 (expertise level: novice vs. experienced) $\times$ 3 (design platform: desktop, MR, and VR) repeated-measures ANOVA on students’ ratings of embodiment and design creativity. The analysis aimed to examine differences in creativity across platforms with different levels of embodiment and between learners with different levels of expertise.

For the behavioral analysis, two researchers analyzed all design activity videos from 34 students across the three experimental conditions. Each design task lasted approximately 10 min. A total of 9226 valid behavioral transition events were coded, including 1733 in the desktop condition, 3373 in the MR condition, and 4120 in the VR condition. The coded data were then analyzed using GSEQ 5.1 to perform LSA and calculate adjusted residuals for significance testing. Significant behavioral sequences were identified based on Z-scores, with higher values indicating a greater likelihood of transition between behaviors. Finally, behavioral transition diagrams were constructed to visualize students’ design behavior patterns.

6. Results

The embodiment and creativity scores were analyzed using repeated-measures ANOVA, with design platform (Desktop, MR, and VR) as the within-subjects factor and expertise level (novice vs. experienced) as the between-subjects factor. Prior to the analyses, the assumptions of normality and homogeneity of variances were examined. Normality was assessed using both the Shapiro–Wilk test and Q–Q plots, which indicated that the embodiment and creativity scores were approximately normally distributed across all experimental conditions. Homogeneity of variances was evaluated using Levene’s test. Although minor violations of homogeneity of variances were observed in some conditions, ANOVA has been shown to be relatively robust to moderate heterogeneity of variances in balanced designs with equal group sizes [52]. Therefore, the data were considered appropriate for subsequent repeated-measures ANOVA. Whenever the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied to adjust the degrees of freedom. The significance level was set at $\alpha = 0.05$ for all statistical analyses.

6.1. Manipulation Check for Sense of Embodiment

A manipulation check was first conducted to verify whether the three design platforms elicited distinct levels of embodiment. All students' overall embodiment scores across the Desktop, MR, and VR conditions were analyzed, with descriptive statistics presented in Table 3.

Table 3. Descriptive Statistics for Sense of Embodiment.

Platforms	Sense of Agency		Sense of Presence		Sense of Embodiment	
	M	SD	M	SD	M	SD
Desktop	1.94	0.82	1.83	0.88	1.88	0.78
MR	3.83	0.76	3.97	0.81	3.90	0.74
VR	4.32	0.67	4.38	0.70	4.34	0.53

Regarding the design platform factor, the results indicated a significant difference in students' sense of embodiment across platforms ($F(2, 64) = 132.177, p < 0.001, \eta^2 = 0.805$). Post hoc multiple comparisons further revealed that the VR condition produced the highest level of embodiment, which was significantly higher than both the MR ($p < 0.005$) and desktop ($p < 0.001$) conditions. This result supports the intended embodiment classification of the three design platforms. Among them, VR, which integrates both bodily interaction and fully immersive virtual environments, achieved the highest level of embodiment. MR showed a reduced level of embodiment due to its limited environmental immersion, whereas the traditional desktop platform exhibited the lowest level of embodiment.

Regarding expertise level, novices reported a significantly higher sense of embodiment than experienced learners ($F(1, 32) = 10.178, p < 0.01, \eta^2 = 0.204$). One possible explanation is that novices, having less prior experience with 3D modeling, may have a greater sensitivity and novelty perception during the design process. In contrast, experienced learners, who possess more professional perspectives and higher expectations for 3D modeling tools, tend to evaluate embodiment more conservatively.

In addition, the interaction effect between design platform and expertise level was not significant ($F(2, 64) = 2.401, p > 0.05, \eta^2 = 0.070$), indicating that no statistically significant interaction between these two factors was observed in the present study. This suggests that, in the present sample, no evidence was found that the effect of design platform on perceived embodiment differed between novice and experienced learners.

6.2. Comparative Analysis of the Creativity of Design Solutions

6.2.1. Analysis of Overall Creativity Scores

Figure 4 presents the overall creativity scores and scores for the seven creativity aspects across the three design platforms for students with different levels of expertise. The overall creativity scores are shown in Figure 4a. The results of the repeated-measures ANOVA revealed significant differences in creativity across the three design platforms ($F(2, 64) = 21.971, p < 0.001, \eta^2 = 0.407$). Post hoc multiple comparisons indicated that creativity scores in both the VR ($p < 0.001$) and MR platform ($p < 0.001$) were significantly higher than those on the desktop platform. This result suggests that higher levels of embodiment may facilitate creativity during design tasks.

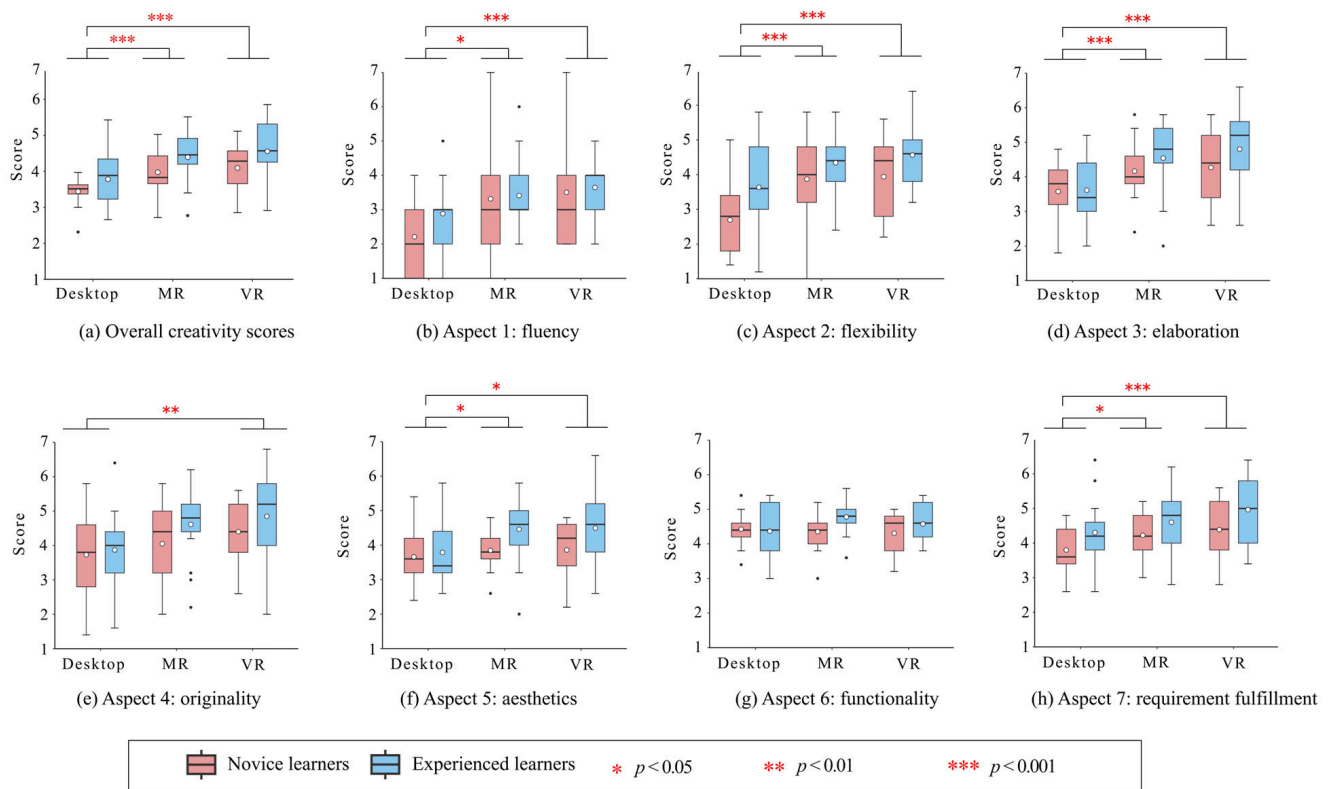


Figure 4. Creativity Scores of Design Solutions. Boxes represent the interquartile range, and horizontal lines indicate medians. White hollow dots represent mean values, while black solid dots indicate outliers.

For expertise level, experienced learners demonstrated significantly higher creativity scores than novice learners ($F(1, 32) = 4.288, p < 0.05, \eta^2 = 0.118$). One possible explanation is that the 3D product design task required a certain level of domain knowledge, which may have enabled experienced learners to draw more effectively on prior knowledge and practical experience when developing their design solutions.

Notably, no significant interaction effect was found between design platform and expertise level ($F(2, 64) = 0.148, p > 0.05, \eta^2 = 0.005$), indicating that the effect of embodied design platforms did not significantly differ between novice and experienced learners in the present sample. This finding suggests that highly embodied design platforms may provide promising opportunities for supporting learners with different levels of expertise in future design education and training.

6.2.2. Analysis of Creativity Scores by Dimension

The effects of design platform and expertise level on the seven aspects of creativity evaluation were further examined, as shown in Figure 4b–h, including fluency, flexibility, elaboration, originality, aesthetics, functionality, and requirement fulfillment. The results of the repeated-measures ANOVA indicated significant differences across design platforms in six aspects: fluency ($F(1.546, 49.460) = 9.269, p < 0.005, \eta^2 = 0.225$), flexibility ($F(2, 64) = 18.860, p < 0.001, \eta^2 = 0.371$), elaboration ($F(2, 64) = 18.535, p < 0.001, \eta^2 = 0.367$), originality ($F(2, 64) = 7.470, p < 0.01, \eta^2 = 0.189$), aesthetics ($F(2, 64) = 5.560, p < 0.05, \eta^2 = 0.148$), and requirement fulfillment ($F(2, 64) = 9.405, p < 0.001, \eta^2 = 0.227$). Post hoc multiple comparisons showed that, across these six dimensions, students consistently achieved significantly higher creativity scores in the VR condition than in the desktop condition, while the MR condition generally showed intermediate performance. These results suggest that the highly embodied VR platform may encourage students

to generate more design ideas, explore a wider range of alternatives, and produce more original solutions. Designs created in VR also tended to be more refined and detailed. In addition, higher scores in aesthetics and requirement fulfillment suggest that the immersive design environment may support the creation of more visually appealing designs while better addressing contextual requirements of the design task. In contrast, no significant differences were found across platforms in functionality, indicating that the level of embodiment provided by the design platform had limited influence on the functional quality of students' design solutions. One possible explanation is that functionality represents a relatively stable dimension of design solutions, depending more on designers' understanding of product requirements and domain knowledge than on the design platform itself. Previous research has similarly suggested that, for conventional products with rather stable functional requirements (e.g., chairs), functionality is less strongly associated with design creativity comparing with other creativity dimensions [53].

For expertise level, experienced learners scored significantly higher than those of novice learners in flexibility ($F(1, 32) = 4.789, p < 0.05, \eta^2 = 0.130$) and requirement fulfillment ($F(1, 32) = 4.414, p < 0.05, \eta^2 = 0.121$). These findings suggest that specialized training in design enables students to develop more flexible design ideas, and better ensure the achievement of design objectives during the creative process.

6.3. Comparative Analysis of Design Behavior Patterns

The coded behavioral sequences from the three design platforms (desktop, MR, and VR) were imported into GSEQ to calculate adjusted residuals (Z-scores), as shown in Table 4. The values represent the differences between the observed and the expected behavioral transition frequencies for the corresponding rows and columns. Following [51], behavioral transition pathway with Z-score greater than 1.96 is considered statistically significant. As shown in Table 4, a total of 38 significant behavioral sequences were identified, including 9 in the desktop condition, 14 in the MR condition, and 15 in the VR condition.

Table 4. Adjusted Residuals (Z-scores).

		A1	A2	A3	A4	A5	A6	B1	B2
Desktop	A1	−7.46	9.29 *	−1.06	1.17	1.39	−4.96	−1.49	−2.73
	A2	1.76	−11.53	0.33	9.25 *	−0.5	−1.06	1.23	3.96 *
	A3	−0.14	1.6	−0.48	1.14	−0.84	−1.53	−0.84	−1.86
	A4	−1.73	8.65 *	3.33 *	−9.15	−0.94	−2.68	0.65	0.68
	A5	6.2 *	−4.3	−0.84	−2.53	3.69 *	0.06	0.24	1.37
	A6	0	0	0	0	0	0	0	0
	B1	10.38 *	−4.19	−1.85	−2.31	−1.37	−1.15	−1.37	0.32
	B2	−0.65	−2.63	−1.86	−1.92	0.11	15.98 *	0.74	−3.43
MR	A1	−7.07	24.83 *	−7.14	−12.23	−1.17	−5.38	−2.84	−5.04
	A2	6.05 *	−27.49	0.67	22.58 *	0.39	−0.29	2.22 *	7.85 *
	A3	−1.64	−0.73	−5.44	7.84 *	−1.74	−2.04	0.18	−0.74
	A4	−8.2	16.18 *	13.04 *	−16.78	0.96	−5.25	−0.19	−5.02
	A5	5.67 *	−4.48	−2.24	−2.25	1.83	5.7 *	0.73	2.06 *
	A6	0	0	0	0	0	0	0	0
	B1	15.66 *	−6.02	−3.14	−4.53	0.5	−2.09	−1.1	2.96 *
	B2	1.51	−5.29	−3.61	−3.88	0.4	26.15 *	0.69	−2.03
VR	A1	−11.72	29.72 *	−8.7	−12.41	−1.23	−5.33	−2.63	−6.06
	A2	8.03 *	−32.6	2.38 *	25.69 *	0.39	−2.65	0.54	10.34 *
	A3	0.19	−0.59	−5.36	6.77 *	−0.19	−3	−0.68	−2.1
	A4	−10.58	19.34 *	12.38 *	−17.52	0.65	−5.17	0.26	−5.41

Table 4. Cont.

		A1	A2	A3	A4	A5	A6	B1	B2
VR	A5	9.37 *	−4.94	−2	−3.79	2.38 *	3.2 *	0.15	1.01
	A6	0	0	0	0	0	0	0	0
	B1	17.9 *	−8.14	−3.15	−4.9	−1.52	0.15	−1.53	2.72 *
	B2	1.81	−5.26	−2.89	−6.14	0.36	29.84 *	5.55 *	−2.79

Note: “*” in the table indicates Z-score > 1.96.

To further visualize students’ design behavior patterns across platforms, behavioral transition diagrams were constructed based on the statistically significant behavioral data (see Figure 5). Separate diagrams were generated for novice and experienced learners under each design platform. In the diagrams, circular nodes represent specific behaviors. Significant behavioral transitions are indicated by lines connecting the nodes, and the direction of the transition is shown by arrows on the lines. The values displayed on the lines represent the Z-scores, and thicker lines indicate higher frequencies. As shown in Figure 5, the desktop platform exhibited fewer significant behavioral transition pathways than the MR and VR platforms, with weaker continuity between different design behaviors. The thickness of the transition lines and the corresponding Z-score values further indicate that the behavioral transitions occurred less frequently on the desktop platform than on the MR and VR platforms. In contrast, VR platforms showed the greatest number of significant transition pathways, together with higher transition frequencies and stronger interconnections among different design behaviors. This suggests that students may have engaged in more complex and dynamic design processes when using the highly embodied platforms.

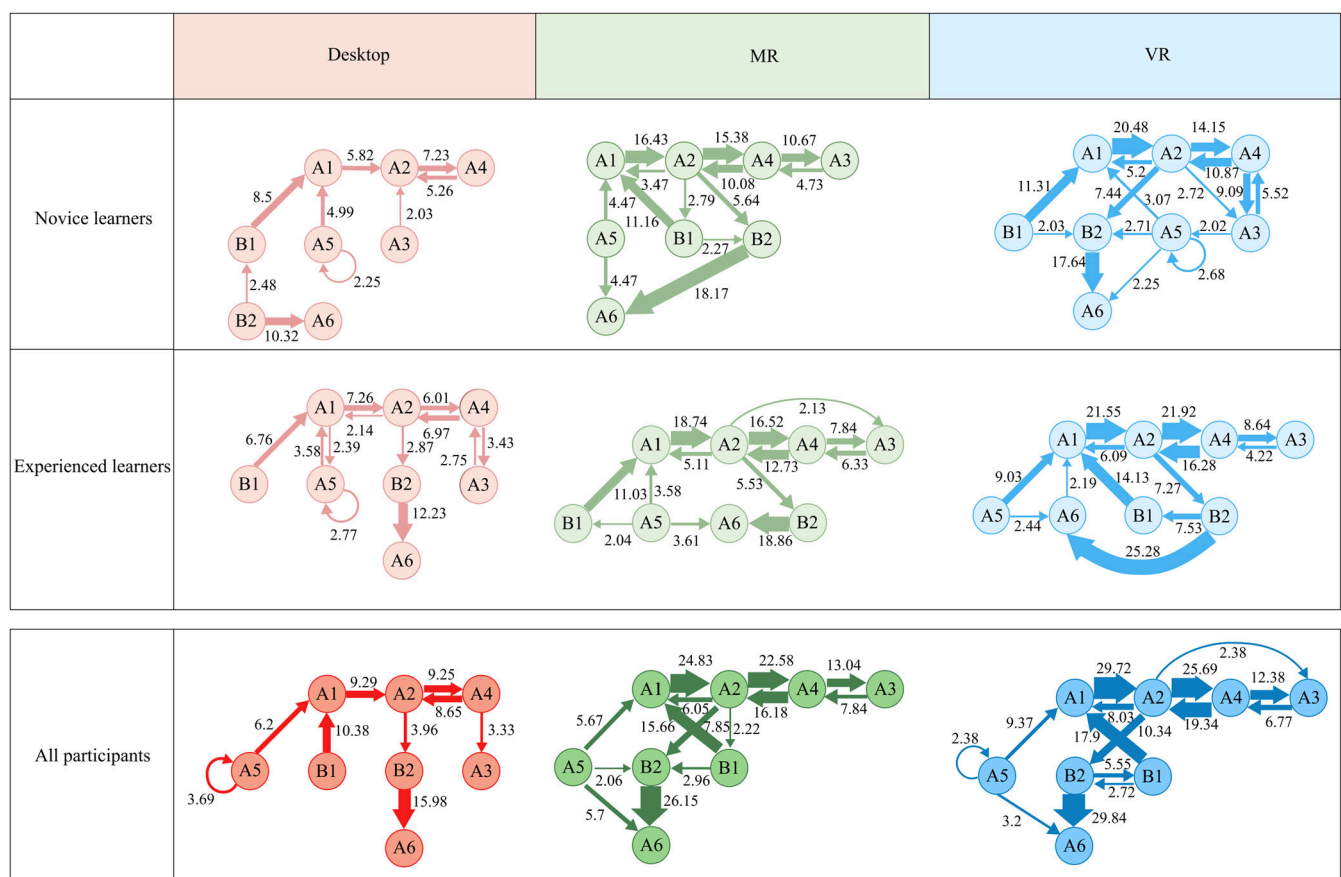


Figure 5. Behavioral Transition Diagrams.

Regarding specific behavioral transition patterns, Figure 5 reveals distinct behavioral characteristics across the three design platforms. Although each platform showed unique transition patterns, the VR and MR conditions have some similarities due to their higher levels of embodiment. For instance, students using both immersive platforms frequently switched bidirectionally among generating (A1), moving (A2), scaling (A4), and rotating (A3) target objects ($A1 \leftrightarrow A2$, Z-score (VR) = 29.72 and 8.03, Z-score (MR) = 24.83 and 6.05; $A2 \leftrightarrow A4$, Z-score (VR) = 25.69 and 19.34, Z-score (MR) = 22.58 and 16.18; $A4 \leftrightarrow A3$, Z-score = 12.38 and 6.77, Z-score (MR) = 13.04 and 7.84). Before generating new objects, students also frequently engaged in deletion ($A5 \rightarrow A1$, Z-score (VR) = 9.37, Z-score (MR) = 5.67) and environmental observation ($B1 \rightarrow A1$, Z-score (VR) = 17.9, Z-score (MR) = 15.66). Compared with the small-scale mouse and keyboard operations required in the desktop platform, the MR and VR platforms allowed students to interact through natural hand gestures and body movements, providing greater sensori-motor engagement. As illustrated in Figure 1, the gesture design of the MR/VR systems was highly consistent with the natural movements people use when manipulating physical objects. Such consistency may have allowed students to map virtual interactions onto their prior design experiences of manipulating real-world objects, thereby facilitating more intuitive design exploration. Consequently, students in the MR and VR conditions engaged in repeated operations, such as moving, scaling, and rotating objects to identify appropriate spatial configurations, as well as generating and deleting objects to compare alternative design ideas. Beyond these shared characteristics, the VR condition demonstrated more frequent and interconnected behavioral patterns than the desktop and MR conditions. Students in VR more frequently alternated among generating (A1), moving (A2), scaling (A4), and rotating (A3) target objects during the design process. They also showed frequent bidirectional transition between observing the environment (B1) and observing their design outcomes (B2), indicating continuous interactions between spatial exploration and design refinement. These findings suggest that the highly embodied VR platform supported more dynamic and exploratory design interactions. Compared with the other two platforms, the distinctive embodiment characteristic of VR lies in its fully immersive design context. As shown in Figure 3, VR provided the highest level of immersion, which may have strengthened students' sense of presence during the design task. Johnson-Glenberg [8] suggested that a stronger sense of presence enables learners to suspend disbelief and engage more actively with the virtual environment. This may explain why students in the VR condition demonstrated more frequent and complex behavioral transitions, as well as more intensive observation of both the design environment and their created objects.

Regarding expertise level, comparisons between novice and experienced learners under each design platform also revealed distinct behavior patterns. On the desktop platform, experienced learners demonstrated a noticeably larger number of significant behavioral transition pathways than novice learners, suggesting that traditional desktop-based may impose a higher learning burden on novices and constrain their design exploration. Previous research has also shown that learners with limited prior knowledge tend to perform more poorly and often require additional instructional support [54]. In contrast, under the MR and VR platforms, the two groups exhibited similar numbers of significant behavioral transition pathways, indicating that higher level of embodiment provided by immersive technology may create a more inclusive design environment. This embodied nature appeared to reduce differences in behavioral adaptation between novice and experienced learners, enabling both groups to engage more readily in free and active design exploration.

7. Discussion and Implications

7.1. *The Role of Embodied Factors in Enhancing Design Creativity in Design Platforms*

Based on both the CAT evaluation of design solutions and the behavioral analysis of the creative process, the findings indicated that higher levels of embodiment positively support creativity. Specifically, students experienced the strongest sense of embodiment on the VR platform, where their design solutions achieved the highest creativity scores and exhibited more frequent and complex design behaviors. In contrast, students in the desktop condition reported lower embodiment and creativity levels and demonstrated relatively simple design behaviors. The MR platform showed intermediate performance between the two. Combined with students' feedback on their design experiences, the study further proposed two potential explanatory embodied factors underlying creativity enhancement in design platforms: action-based metaphors and contextual consistency.

7.1.1. Action-Based Metaphors

In the VR and MR platforms, students completed the design tasks through gestures and bodily movements. Interactions such as moving and scaling (see Figure 1) virtual objects were designed to resemble common real-world actions. Many participants described the interaction experiences as similar to playing with building blocks or shaping clay. For example, one participant stated, "When I grab or move virtual objects with my hands, it feels like playing with building blocks, which allows me to fully engage in the activity" (Participant 9). These embodied interactions, which draw on metaphors from everyday experiences in the real world, may easily activate cognitive associations related to creative design. As a result, students may approach the design task in a more intuitive and relaxed state, which helps stimulate their creative potential. Several participants also reported that bodily interaction helped stimulate new ideas during the design process. As one student explained, "Although I had an initial design idea, adjusting objects with my hands often led to new ideas. Rapid changes in body movements stimulated new thoughts and made my thinking more flexible" (Participants 22 and 30). Previous research has also shown that switching between left and right hands can metaphorically activate shifts in cognitive perspectives, helping individuals break fixed patterns of thinking [55]. In addition, fluid and fluent movements during creative tasks can metaphorically enhance creative processing [56,57]. Consistent with these findings, the behavioral analysis in this study showed that students in the VR and MR conditions exhibited more frequent and interconnected behavioral transitions, potentially reflecting more exploratory and flexible design cognitive process. These findings suggest that the embodied experiences in immersive platforms may strengthen the connection between bodily experience and abstract design thinking, which may in turn facilitate creativity.

7.1.2. Contextual Consistency

In desktop design platforms, interaction and visualization occurred in separate spaces. Students interacted with the system using keyboard and mouse, while design objects were presented on a 2D screen. In contrast, VR and MR platforms integrated interaction and visualization within the same spatial context. In particular, the VR platform provided immersive virtual scenes aligned with the design task context (e.g., a "public reading space"). This may have allowed students to more intuitively perceive the relationship between the product and its surrounding environment and facilitated the activation of real-world experiences. For example, one participant commented, "I felt fully immersed in the public reading space, as if my body was part of the environment. After completing a design, I even wanted to physically sit there and experience what it felt like" (Participant 10). Behavioral analysis further showed that the "Observe Environment ↔ Observe Solutions"

transition occurred more frequently in the VR condition. This suggests that contextual consistency may facilitate the use of environmental cues during design thinking, thereby transforming them into creative ideas. Neisser (2014) [58] also argued that perception is a real-time process that occurs within specific environmental contexts and is closely linked to situational factors. The present findings therefore suggest that contextual consistency may promote coordination between design cognition and the surrounding environment, helping students draw on embodied experience during design activities and potentially facilitating creativity.

7.2. Practical Implications

The findings of this study suggest that the development of design platforms should move beyond a purely technological focus toward a deeper integration of embodied cognition and instructional design, in order to better support students' creativity. Practical implications are discussed from three perspectives: platform design, learner differences, and pedagogical strategies.

7.2.1. Design Considerations for Embodied Design Platforms

Most existing design platforms remain predominantly visually oriented, with interaction largely relying on indirect control methods such as keyboards, mice, or handheld controllers. This may lead to a disconnection between learners' bodily engagement and cognitive processes. The present findings indicate that higher levels of embodiment may contribute to enhanced creativity. Future design platforms should therefore strengthen embodiment through both bodily interaction and environmental context. First, system interactions could establish intuitive mappings with real-world activities to support more natural and direct bodily engagement during design tasks. Such sensori-motor involvement may stimulate creative thinking through embodied experience, which is consistent with the view that cognitive processes are grounded in perceptual and motor systems [59]. Second, immersive environments could be aligned with design tasks to provide contextually consistent experiences. This alignment may support learners' situational understanding and foster creative thinking by situating design activities within meaningful contexts.

7.2.2. Supporting Creativity Across Different Learner Expertise Levels

The results showed no significant interaction between design platform and expertise level, suggesting that highly embodied design platforms may enhance creativity among both novice and experienced learners. However, differences in creative performance across expertise levels indicate that learners may demonstrate distinct cognitive characteristics within embodied learning environments. These findings suggest that embodied design platforms have the potential to support different stages of design education as effective tools of creative practice. At the same time, instructional support should be adapted to learners' cognitive characteristics. Specifically, novice learners tend to rely more heavily on concrete experience. According to experiential learning theory [60], platforms could therefore provide direct sensory feedback (e.g., tactile sensation of virtual materials) and intuitive interfaces to support knowledge construction through embodied experience. In contrast, experienced learners are more capable of abstract reasoning and integration based on existing knowledge structures [60]. Accordingly, design systems could offer higher-level tools, such as parametric control and structural visualization to facilitate the integration of embodied experience with conceptual knowledge, thereby supporting more complex design exploration and innovation.

7.2.3. Pedagogical Strategies for Embodied Design Platforms

The integration of embodied design platforms represents not only a technological advancement but also a transformation in design pedagogy. Rather than simply transferring traditional instructional content into virtual environments, educators may need to reconsider teaching roles, instructional competencies, and assessment approaches within embodied learning contexts. First, teachers should shift from the role of knowledge transmitters to facilitators who support students' active exploration through embodied learning environments. Second, educators also need to develop new instructional competencies. In addition to mastering platform functionalities, a deeper understanding of the embodied characteristics of immersive environments may help educators design learning activities that more effectively foster creative thinking. Finally, assessment strategies should be adapted accordingly. Beyond evaluating final design solutions, incorporating process-oriented measures, such as design behavioral patterns, can provide a more comprehensive evaluation of students' creativity and problem-solving abilities. Aligning pedagogical strategies with the affordances of embodied platforms may help educators more fully realize their potential for fostering creativity in design education.

8. Conclusions

This study provides preliminary empirical evidence for the effectiveness of embodied design platforms in enhancing students' design creativity. The findings offer both theoretical insights and practical implications for the digital transformation of design education. A major contribution of this research is that it explores the potential of integrating embodied cognition theory into the development of design platforms, extending current perspectives on digital technology in design education. In doing so, the study highlights the interrelationships among design thinking, design behavior, and digital technologies. The findings suggest that higher levels of embodiment may facilitate creative performance within digital design platforms. In particular, action-based metaphor and contextual consistency emerged as two potential explanatory factors that may help interpret how embodied platforms influence creativity. These insights offer practical implications for the design of embodied platforms, the accommodation of learner differences, and the development of pedagogical strategies in future design education.

9. Limitations and Future Work

Despite these contributions, several limitations should be acknowledged. First, due to technical constraints, the present study focused primarily on early-stage conceptual design tasks. Future work should extend the investigation to broader phases of the design process, including iteration and evaluation. Second, the behavioral coding scheme focused on observable design actions (e.g., move, rotate, and scale) to identify behavioral transition patterns across different platforms. However, it did not distinguish the cognitive strategies underlying individual actions, such as exploratory, corrective, or goal-directed behaviors. Future research could combine fine-grained behavioral analysis with cognitive measures to investigate how embodied platforms influence the evolution of design cognitive strategies. Third, several individual and experimental factors may have influenced participants' performance across platforms. These include individual differences in digital literacy, learning effects from repeated tasks, and participant fatigue. In addition, potential simulator sickness and the novelty of immersive technologies may have affected participants' experiences and creative performance. Although the order of conditions was counterbalanced, and standardized training and practice tasks were provided, these factors cannot be completely ruled out. Future studies could control participants' prior experience more systematically, adopt longer-term exposure, and

monitor simulator sickness and fatigue to further isolate the effects of embodiment. Fourth, this study mainly examined design creativity, while the potential impact of embodied platforms on other learning outcomes, such as collaboration, engagement and learning quality, remains to be explored. Future research should further integrate embodied cognition with theories of knowledge construction to develop a more comprehensive theoretical framework for embodied digital education platforms, thereby providing sustained support for cultivating innovative design talents.

Author Contributions: Conceptualization, W.W. and Z.L.; methodology, W.W., Z.L., S.Y., H.Y., F.X., and L.Y.; software, H.Y. and F.X.; validation, W.W., S.Y., H.Y. and F.X.; formal analysis, W.W. and S.Y.; investigation, W.W. and S.Y.; resources, W.W., Z.L., S.Y., H.Y., F.X., and L.Y.; data curation, W.W. and S.Y.; writing—original draft preparation, W.W. and S.Y.; writing—review and editing, W.W., S.Y., and Z.L.; visualization, W.W. and S.Y.; supervision, Z.L., L.Y. and Y.Z.; project administration, Z.L.; funding acquisition, Z.L. and Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (52275234), the Humanities and Social Sciences Foundation of the Ministry of Education of China (22YJA760055), and the Science and Technology Innovation Program Project of Beijing Institute of Technology (2024CX01023).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Beijing Institute of Technology Ethics Committee (Approval No. BIT-EC-H-115). The anonymity and confidentiality of the participants were guaranteed, and participation was completely voluntary.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented are available on request from the corresponding author.

Acknowledgments: We thank all participants for their commitment to research.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Runco, M.A.; Jaeger, G.J. The Standard Definition of Creativity. *Creat. Res. J.* **2012**, *24*, 92–96. [\[CrossRef\]](#)
2. Astatke, M.; Weng, C.; Yohannes, A. What Is the Role of Immersive Virtual Reality (IVR) in the Development of Creativity Skills and Engagement among Students in STREAM (Science, Technology, Religion, Engineering, Art, and Mathematics)-Based Learning? *Educ. Inf. Technol.* **2025**, *30*, 21403–21425. [\[CrossRef\]](#)
3. Wu, P.; Liu, Y.; Chen, H.; Li, X.; Wang, H. VR-Empowered Interior Design: Enhancing Efficiency and Quality through Immersive Experiences. *Displays* **2025**, *86*, 102887. [\[CrossRef\]](#)
4. Chang, Y.-S.; Kao, J.-Y.; Wang, Y.-Y. Influences of Virtual Reality on Design Creativity and Design Thinking. *Think. Ski. Creat.* **2022**, *46*, 101127. [\[CrossRef\]](#)
5. Foglia, L.; Wilson, R.A. Embodied Cognition. *Wiley Interdiscip. Rev. Cogn. Sci.* **2013**, *4*, 319–325. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Antle, A.N.; Corness, G.; Droumeva, M. What the Body Knows: Exploring the Benefits of Embodied Metaphors in Hybrid Physical Digital Environments. *Interact. Comput.* **2009**, *21*, 66–75. [\[CrossRef\]](#)
7. Pillat, R.; Nagendran, A.; Lindgren, R. Design Requirements for Using Embodied Learning and Whole-Body Metaphors in a Mixed Reality Simulation Game. In Proceedings of the 2012 IEEE International Symposium on Mixed and Augmented Reality-Arts, Media, and Humanities (ISMAR-AMH), Atlanta, GA, USA, 5–8 November 2012; pp. 105–106.
8. Johnson-Glenberg, M.C. Immersive VR and Education: Embodied Design Principles That Include Gesture and Hand Controls. *Front. Robot. AI* **2018**, *5*, 375272. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Fechter, M.; Schleich, B.; Wartzack, S. Comparative Evaluation of WIMP and Immersive Natural Finger Interaction: A User Study on CAD Assembly Modeling. *Virtual Real.* **2022**, *26*, 143–158. [\[CrossRef\]](#)
10. Obeid, S.; Demirkan, H. The Influence of Virtual Reality on Design Process Creativity in Basic Design Studios. *Interact. Learn. Environ.* **2023**, *31*, 1841–1859. [\[CrossRef\]](#)
11. Samaniego, M.; Usca, N.; Salguero, J.; Quevedo, W. Creative Thinking in Art and Design Education: A Systematic Review. *Educ. Sci.* **2024**, *14*, 192. [\[CrossRef\]](#)

12. Amabile, T.M. Social Psychology of Creativity: A Consensual Assessment Technique. *J. Pers. Soc. Psychol.* **1982**, *43*, 997. [[CrossRef](#)]
13. Baer, J.; Kaufman, J.C. Assessing Creativity with the Consensual Assessment Technique. In *The Palgrave Handbook of Social CREATIVITY Research*; Springer: Cham, Switzerland, 2018; pp. 27–37.
14. Cheng, L.; Wang, M.; Chen, Y.; Niu, W.; Hong, M.; Zhu, Y. Design My Music Instrument: A Project-Based Science, Technology, Engineering, Arts, and Mathematics Program on the Development of Creativity. *Front. Psychol.* **2022**, *12*, 763948. [[CrossRef](#)] [[PubMed](#)]
15. Suwa, M.; Tversky, B. What Do Architects and Students Perceive in Their Design Sketches? A Protocol Analysis. *Des. Stud.* **1997**, *18*, 385–403. [[CrossRef](#)]
16. Torrance, E.P. *Torrance Tests of Creative Thinking—Norms Technical Manual Research Edition—Verbal Tests, Forms A and B—Figural Tests, Forms A and B*; Personnel Press: Princeton, NJ, USA, 1966.
17. Torrance, E.P. *Torrance Tests of Creative Thinking Norms-Technical Manual*; Personnel Press: Lexington, MA, USA, 1974.
18. Lu, Z. A Research on Thinking Mechanism in Fuzzy Front End of Car Styling. *Automot. Eng.* **2017**, *39*, 517–523. (In Chinese)
19. Kim, M.J.; Maher, M.L. The Impact of Tangible User Interfaces on Spatial Cognition during Collaborative Design. *Des. Stud.* **2008**, *29*, 222–253. [[CrossRef](#)]
20. Yang, X.; Cheng, P.-Y.; Lin, L.; Huang, Y.M.; Ren, Y. Can an Integrated System of Electroencephalography and Virtual Reality Further the Understanding of Relationships between Attention, Meditation, Flow State, and Creativity? *J. Educ. Comput. Res.* **2019**, *57*, 846–876. [[CrossRef](#)]
21. Rashevskaya, N.V.; Semerikov, S.O. From Philosophical Immersion to Digital Reality: A Unified Theoretical Framework for Understanding and Classifying Immersive Technologies in Education. *Comput. Educ. X Real.* **2026**, *8*, 100147. [[CrossRef](#)]
22. Liu, Z.; Wang, L. Study on the Style Construction of Embodied Cognitive Learning Supported by VR Technology. *Educ. Inf. Technol.* **2025**, *30*, 403–419. [[CrossRef](#)]
23. Suo, X.; Yin, B.; Feng, X. Augmented Reality and Embodied Learning: Effects of Embodiment Degrees on Students' Learning Achievement, Cognitive Load, and Technology Acceptance. *Front. Psychol.* **2026**, *16*, 1712261. [[CrossRef](#)] [[PubMed](#)]
24. Vergara, D.; Lorenzo, M.; Rubio, M.P. Virtual Environments in Materials Science and Engineering: The Students' Opinion. In *Handbook of Research on Recent Developments in Materials Science and Corrosion Engineering Education*; IGI Global Scientific Publishing: Hershey, PA, USA, 2015; pp. 148–165.
25. Tang, Y.-M.; Au, K.M.; Lau, H.C.; Ho, G.T.; Wu, C.-H. Evaluating the Effectiveness of Learning Design with Mixed Reality (MR) in Higher Education. *Virtual Real.* **2020**, *24*, 797–807. [[CrossRef](#)]
26. Guan, J.-Q.; Wang, W.-Z.; Wang, X.-F.; Zhu, J.; Hwang, G.-J. Effects of a VR-Based Collaborative Painting Approach on Primary Students' Creativity and Collaborative Quality in Art Courses. *Educ. Technol. Res. Dev.* **2024**, *72*, 2187–2211. [[CrossRef](#)]
27. Ye, H. Embodied Cognition: A New Approach in Cognitive Psychology. *Adv. Psychol. Sci.* **2010**, *18*, 705–710. (In Chinese)
28. Kougioumtzis, K. Embodied Cognition in STEM Learning: An Integrative Review of Conceptualizations, Mechanisms, and Boundary Conditions. *Front. Educ.* **2026**, *11*, 1811569. [[CrossRef](#)]
29. Clark, A.; Chalmers, D. The Extended Mind. *Analysis* **1998**, *58*, 7–19. [[CrossRef](#)]
30. Clark, A. *Supersizing the Mind: Embodiment, Action, and Cognitive Extension*; Oxford University Press: Oxford, UK, 2010.
31. Wu, X.; Liang, J.; Yu, Y.; Li, G.; Yen, G.G.; Yu, H. Embodied Perception Interaction, and Cognition for Wearable Robotics: A Survey. *IEEE Trans. Cogn. Dev. Syst.* **2024**, *18*, 57–74. [[CrossRef](#)]
32. Crivelli, D.; Balconi, M. Industrial Collaborative Robotics, Humanoid Cobots, and Social Embodiment: A Critical Look on Human–Robot Interaction. *Int. J. Humanoid Robot.* **2025**, *22*, 2430001. [[CrossRef](#)]
33. Chen, J.; Ning, C.; Chen, C. A Systematic Literature Review of Virtual Embodied Experience. *Psychol. Mark.* **2023**, *40*, 2167–2185. [[CrossRef](#)]
34. Guy, M.; Normand, J.-M.; Jeunet-Kelway, C.; Moreau, G. The Sense of Embodiment in Virtual Reality and Its Assessment Methods. *Front. Virtual Real.* **2023**, *4*, 1141683. [[CrossRef](#)]
35. Kiltner, K.; Groten, R.; Slater, M. The Sense of Embodiment in Virtual Reality. *Presence Teleoperators Virtual Env.* **2012**, *21*, 373–387. [[CrossRef](#)]
36. Dufresne, F.; Dubosc, C.; Lefrou, T.; Gorisse, G.; Christmann, O. Am I (Not) a Ghost? Leveraging Affordances to Study the Impact of Avatar/Interaction Coherence on Embodiment and Plausibility in Virtual Reality. *IEEE Trans. Vis. Comput. Graph.* **2025**, *31*, 2611–2621. [[CrossRef](#)] [[PubMed](#)]
37. Ergun, B.G.; Şahiner, R. Embodiment in Virtual Reality and Augmented Reality Games: An Investigation on User Interface Haptic Controllers. *J. Soft Comput. Artif. Intell.* **2023**, *4*, 80–92. [[CrossRef](#)]
38. Wenk, N.; Penalver-Andres, J.; Buetler, K.A.; Nef, T.; Müri, R.M.; Marchal-Crespo, L. Effect of Immersive Visualization Technologies on Cognitive Load, Motivation, Usability, and Embodiment. *Virtual Real.* **2023**, *27*, 307–331. [[CrossRef](#)] [[PubMed](#)]
39. Hii, C.-H.; Yang, C.-C. Comparing the Application Effects of Immersive and Non-Immersive Virtual Reality in Nursing Education: The Influence of Presence and Flow. *Nurs. Rep.* **2025**, *15*, 149. [[CrossRef](#)] [[PubMed](#)]

40. Bybee, R.W.; Buchwald, C.E.; Crissman, S.; Heil, D.R.; Kuerbis, P.J.; Matsumoto, C.; McInerney, J.D. *Science and Technology Education for the Elementary Years: Frameworks for Curriculum and Instruction*; National Center for Improving Science Education: Washington, DC, USA, 1989.
41. Slater, M. Place Illusion and Plausibility Can Lead to Realistic Behaviour in Immersive Virtual Environments. *Philos. Trans. R Soc. B Biol. Sci.* **2009**, *364*, 3549–3557. [[CrossRef](#)] [[PubMed](#)]
42. Slater, M.; Wilbur, S. A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence Teleoperators Virtual Environ.* **1997**, *6*, 603–616. [[CrossRef](#)]
43. Blanke, O.; Metzinger, T. Full-Body Illusions and Minimal Phenomenal Selfhood. *Trends Cogn. Sci.* **2009**, *13*, 7–13. [[CrossRef](#)] [[PubMed](#)]
44. Eubanks, J.C.; Moore, A.G.; Fishwick, P.A.; McMahan, R.P. A Preliminary Embodiment Short Questionnaire. *Front. Virtual Real.* **2021**, *2*, 647896. [[CrossRef](#)]
45. Johnson-Glenberg, M.C.; Bartolomea, H.; Kalina, E. Platform Is Not Destiny: Embodied Learning Effects Comparing 2D Desktop to 3D Virtual Reality STEM Experiences. *J. Comput. Assist. Learn.* **2021**, *37*, 1263–1284. [[CrossRef](#)]
46. Lessiter, J.; Freeman, J.; Keogh, E.; Davidoff, J. A Cross-Media Presence Questionnaire: The ITC-Sense of Presence Inventory. *Presence Teleoperators Virtual Environ.* **2001**, *10*, 282–297. [[CrossRef](#)]
47. Song, X. A Consensual Technique for Creativity Assessment. *Adv. Psychol. Sci.* **2005**, *13*, 37–42. (In Chinese)
48. Guilford, J.P. Creativity. *Am. Psychol.* **1950**, *5*, 444–454. [[CrossRef](#)] [[PubMed](#)]
49. Casakin, H.; Kreitler, S. Evaluating Creativity in Design Problem Solving. In Proceedings of the Wonderground–DRS International Conference, Lisbon, Portugal, 1–4 November 2006.
50. Christensen, B.T.; Ball, L.J. Dimensions of Creative Evaluation: Distinct Design and Reasoning Strategies for Aesthetic, Functional and Originality Judgments. *Des. Stud.* **2016**, *45*, 116–136. [[CrossRef](#)]
51. Bakeman, R.; Gottman, J.M. *Observing Interaction: An Introduction to Sequential Analysis*; Cambridge University Press: Cambridge, UK, 1997.
52. Glass, G.V.; Peckham, P.D.; Sanders, J.R. Consequences of Failure to Meet Assumptions Underlying the Fixed Effects Analyses of Variance and Covariance. *Rev. Educ. Res.* **1972**, *42*, 237–288. [[CrossRef](#)]
53. Han, J.; Forbes, H.; Schaefer, D. An Exploration of How Creativity, Functionality, and Aesthetics Are Related in Design. *Res. Eng. Des.* **2021**, *32*, 289–307. [[CrossRef](#)]
54. Han, J.; Liu, G.; Zheng, Q. Prior Knowledge as a Moderator between Signaling and Learning Performance in Immersive Virtual Reality Laboratories. *Front. Psychol.* **2023**, *14*, 1118174. [[CrossRef](#)] [[PubMed](#)]
55. Leung, A.K.; Kim, S.; Polman, E.; Ong, L.S.; Qiu, L.; Goncalo, J.A.; Sanchez-Burks, J. Embodied Metaphors and Creative “Acts”. *Psychol. Sci.* **2012**, *23*, 502–509. [[CrossRef](#)] [[PubMed](#)]
56. Slepian, M.L.; Ambady, N. Fluid Movement and Creativity. *J. Exp. Psychol. Gen.* **2012**, *141*, 625. [[CrossRef](#)] [[PubMed](#)]
57. Wang, W. Exploring the Effects of Embodied Interaction on Creative Thinking Based on Neurophysiological Measures. *J. Mech. Eng.* **2025**, *61*, 237–248. (In Chinese) [[CrossRef](#)]
58. Neisser, U. *Cognitive Psychology: Classic Edition*; Psychology Press: Hove, UK, 2014.
59. Barsalou, L.W. Grounded Cognition. *Annu. Rev. Psychol.* **2008**, *59*, 617–645. [[CrossRef](#)] [[PubMed](#)]
60. Kolb, D.A. *Experiential Learning: Experience as the Source of Learning and Development*; FT Press: Upper Saddle River, NJ, USA, 2014.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.