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RESEARCH ARTICLE

Enhancing Learners' Convergence Competency through VR Design-Based STEAM Education

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ABSTRACT

This study explores the impact of integrating virtual reality (VR) technology into design-oriented STEAM education on students' convergence competency. The main aim was to enhance learners' abilities to generate innovative solutions, engage in scientific inquiry, and develop design skills through VR-supported design activities. Specifically, the study examined the effects of VR integration, potential gender differences in learning outcomes, and students' satisfaction and intention to continue with VR-based STEAM learning. A total of 345 elementary and secondary school students participated in the study where they designed VR artifacts to address various socio-scientific issues. For data collection, pre- and post-surveys were conducted to assess changes in convergence competency. Statistical analyses revealed significant overall gains in convergence competency, with no significant gender differences. Most students expressed high satisfaction and a strong intention to continue VR-integrated STEAM education, particularly younger learners. These findings demonstrate the potential of VR to enrich design-oriented STEAM education, promote convergence competency, and advance gender-equitable learning opportunities.

Keywords: Convergence competency, design skills, design-oriented STEAM education, virtual reality, gender disparity

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Introduction

The primary goal of STEAM (Science, Technology, Engineering, Arts, and Mathematics) education is to cultivate students' ability to think critically, creatively, and integratively across disciplines in order to solve real-world problems. However, despite sustained efforts to promote STEAM education, the alignment between policy goals and classroom practices remains unclear and inconsistent. Prior studies have reported that STEAM lessons frequently involve only surface-level subject integration or fragmented activities, rather than sustained interdisciplinary implementation (Kwon et al., 2021). Teachers have also identified the absence of clear guidance and effective pedagogical models as a major barrier to fostering students' core competencies in STEAM education (Falls, 2020).

In response to these challenges, this study examines the potential of design-oriented

STEAM education to foster students' convergence competency, which is to integrate knowledge, skills, and ways of thinking across multiple disciplines to generate creative and socially meaningful solutions to complex problems. Two perspectives frame this research study. First, design activities are employed to address complex socio-scientific issues (SSI) in STEAM education. Over the past decade, increasing attention has been given to encouraging learners' social participation and engagement with societal issues through creative expression (Kim et al., 2022). Likewise, integrating SSI into STEAM education has been shown to enhance scientific literacy and support meaningful learning (Altan et al., 2018; Wahono et al., 2021). Second, the study emphasizes students' roles as active creators rather than passive consumers of knowledge. STEAM provides a framework for cultivating 21st-century competencies while enriching learning by integrating creative practices into science and technology (Katz-Buonincontro, 2018; Mang et al., 2021). Within this context, virtual reality (VR) is highlighted as both an expressive medium and a problem-solving space. Prior research has demonstrated that VR-based STEAM environments can positively influence learning outcomes and motivation (Pellas et al., 2020). By engaging students in the design of virtual spaces, it is anticipated that they will expand both their creative expression and convergence thinking skills.

Building on this rationale, the present study implements and evaluates the effects of VR-integrated, design-oriented STEAM education on students' convergence competency. The STEAM classes were designed to empower students to create VR artifacts that address complex socio-scientific issues. It was hypothesized that engaging in VR design activities to tackle SSI would enhance students' interdisciplinary knowledge and skills, which are fundamental to STEAM education. The study focused on three dimensions of convergence competency: core skills, scientific inquiry, and design skills. In addition, it examined potential gender differences, students' satisfaction, and their intention to continue participating in VR-based STEAM activities, thereby addressing the importance of both gender equity and sustained engagement in STEAM education. The research was guided by the following questions:

1. How do design-oriented STEAM lessons with VR impact students' convergence competency?
2. Are there significant gender differences in convergence competency outcomes within design-oriented STEAM lessons with VR?
3. How do students perceive satisfaction and continuance intention regarding design-oriented STEAM lessons with VR?

Theoretical Background

Convergence Competency in STEAM Education

Recognizing the lack of clear definitions and frameworks in STEM education, Quinn et al. (2020) propose a convergence model that illustrates how different disciplinary areas interact to form core knowledge and inquiry practices. The concept of convergence is essential in STEAM education, where STEM is expanded through the integration of the arts and humanities. In general, convergence competency refers to the ability to integrate disciplinary values and knowledge across multiple fields (So et al., 2019). Its definition can vary depending on curricular goals, the nature of integrated knowledge, and the inquiry practices involved. Given this study's focus on integrating socio-scientific issues and designing VR to address real-world problems, the following section reviews literature related to three dimensions of convergence competency: core skills, scientific inquiry, and design skills.

Core skills in STEAM education mean equipping students to tackle real-world problems by synthesizing interdisciplinary knowledge. These include communication, collaboration, and convergence thinking, which are fundamental abilities for integrating and expressing knowledge across fields. Since STEAM education frequently involves project-based learning and collaborative learning, effective communication and collaboration are critical for problem-solving that exceeds individual capacity (Chen & Ding, 2023). Convergence thinking, which is the capacity to synthesize diverse elements into novel solutions (de Vries & Lubart, 2017), is also indispensable as a core skill. Within STEAM contexts, students must draw upon science, technology, arts, and mathematics to generate innovative outcomes and address complex issues (Perales & Aróstegui, 2024).

Scientific inquiry represents another essential dimension of convergence competency. It involves systematically exploring problems through processes such as identifying questions, formulating hypotheses, designing experiments, collecting and analyzing data, and drawing generalizations (Martin, 2001). In STEAM education, inquiry-based skills, ranging from observation and classification to inference, communication, and conclusion-drawing, are vital for addressing real-world challenges (Althouse, 1988; Bassachs et al., 2020; Lind, 2005). Framing inquiry around socio-scientific issues (SSI) further encourages students to apply scientific concepts to authentic contexts, thereby strengthening scientific literacy (Reswara et al., 2024). Viehmann et al. (2024) suggest that in STEAM education, scientific inquiry is often employed to equip students to address complex real-world problems, thereby fostering interdisciplinary exploration.

Design skills extend this integration by emphasizing the ability to ideate, prototype, and evaluate solutions (Dong, 2008). The American Institute of Graphic Arts (AIGA) defines design skills broadly, encompassing communication, problem-solving, tool usage, and human-centered approaches. Prior studies have shown that incorporating design activities into STEAM learning not only enhances students' convergence thinking but also improves their attitudes toward interdisciplinary learning (Hyun et al., 2022). In the context of this study, design skills specifically refer to students' ability to translate ideas into VR artifacts, thereby using immersive design as a medium for problem-solving.

Virtual Reality in STEAM Education

Virtual Reality (VR) is a computer-generated immersive environment that integrates components such as computer graphics, information processing, networking, and audio to enable advanced human–machine interactions. With the advent of lightweight head-mounted displays (HMDs) and precise motion recognition technologies, VR has become a widely adopted platform across multiple fields (Martín-Gutiérrez et al., 2017). In education, VR provides learners with immersive experiences that are difficult or impossible to replicate in real life. Beyond passive observation, it allows students to actively participate as creators in problem-centered lessons, fostering exploration, analysis, and production through interactive applications. Research consistently highlights VR's capacity to increase learner motivation and engagement by offering highly interactive and immersive experiences (Chen & Hsu, 2020; Martín-Gutiérrez et al., 2017; Soto et al., 2020).

Recent trends further demonstrate a growing interest in integrating immersive technologies such as VR and augmented reality (AR), into STEAM education (Shu & Huang, 2021). This reflects increasing recognition of their potential to support interdisciplinary learning by bridging abstract concepts with experiential activities. In STEM contexts, VR has been shown to address persistent challenges such as over-reliance on theoretical instruction and limited opportunities for hands-on exploration (Yun, 2023). By providing participatory and immersive experiences, VR enables students to actively engage with scientific and technological content in more meaningful ways (Yoo & Kim, 2019).

Importantly, the use of VR in education extends beyond enhancing motivation and engagement. VR can also foster higher-order thinking skills such as creativity, convergence thinking, and critical thinking. A key strategy is to engage students not only as consumers but also as creators of VR artifacts. For example, Bae et al. (2018) reported that students' interest in science and technology increased when they designed virtual botanical gardens in STEAM classes. Similarly, Cho and Kim (2019) found that immersive VR-based STEAM lessons strengthened students' problem-solving processes and improved collaboration in group activities. These findings suggest that VR, when positioned as a design and creation tool, has the potential to enrich STEAM education by cultivating interdisciplinary skills and higher-order competencies.

Gender in STE(A)M Education

The persistent underrepresentation of women in the STEM workforce, alongside lower interest and achievement among female students, continues to be a pressing concern in both education and society. Given that STEAM education emphasizes collaboration and group interaction, the gender composition of learning groups has been identified as a significant factor influencing students' behaviors and achievement (Yen et al., 2021).

Several studies suggest that gender dynamics meaningfully shape learning processes in STEAM contexts. Ma et al. (2022), for example, examined the impact of gender composition by assigning elementary students to boy-only, girl-only, and mixed-gender groups. Their analysis of cognitive, interactive, and emotional responses revealed that group composition had a stronger influence on students' behavioral performance than individual gender differences. In particular, mixed-gender groups demonstrated advantages in higher-order thinking, interaction, and emotional expression, underscoring the benefits of fostering gender-diverse collaboration in STEAM classrooms. Similarly, Lee et al. (2021) implemented a STEAM program with 399 elementary students to enhance creativity, communication, and problem-solving skills. Their findings indicated that female students scored significantly higher than male students in attitudes toward STEAM, including interest, communication, self-concept, and consideration of science and engineering careers. The researchers suggested that the program's emphasis on affective experiences, sharing, and collaboration had contributed to these gender-based differences in attitudes.

In contrast, other studies report that gender may not play a significant role in shaping learning outcomes in STEAM education. Yen et al. (2021) investigated gender differences in engineering design thinking through a project-based STEAM program with 137 high school students (75 male, 62 female). Over 10 weeks, students engaged in lessons on earthquake safety, analyzed truss structures, and constructed truss towers using CAD software and 3D printers. Both male and female students demonstrated significant improvements in engineering design thinking, with no significant gender differences in their outcomes.

Taken together, these findings illustrate a complex picture: while gender composition and program design can influence student attitudes, interactions, and group behaviors in STEAM education, gender does not always translate into differences in measurable learning outcomes. This suggests that the effects of gender in STEAM contexts are likely mediated by instructional design, learning environment, and the nature of collaborative activities.

Methods

Participants and Research Context

This study was conducted as part of a larger project aimed at developing STEAM programs to foster students' convergence competency. A total of 363 students participated, including 151 from one elementary school and 212 from two middle schools. Participants were recruited through convenience sampling from teachers involved in the STEAM project to co-develop the VR-integrated STEAM program. Teachers who expressed interest in implementing the program joined the study with their students and collaborated with STEAM education experts to design the lessons.

In the elementary school, the program was implemented by homeroom teachers, whereas in the middle schools, science, technology, and art teachers coordinated across their respective subjects to deliver the program collaboratively. Participants were categorized into four groups by grade level: Group 1 (elementary, 3rd–4th grades), Group 2 (elementary, 5th–6th grades), Group 3 (all middle school grades), and Group 4 (middle school, 2nd grade). For Group 3, as the study was conducted as part of the free-learning semester program, the group includes students from all grade levels. In elementary schools, homeroom teachers led the lessons, while in middle schools, science, technology, and design teachers co-facilitated. None of the teachers or students had prior experience with VR-integrated STEAM education. To ensure readiness, the research team conducted professional development sessions for teachers, focusing on STEAM pedagogy and the technological tools required for implementation.

To evaluate the program's impact, students completed pre- and post-surveys measuring changes in their convergence competency. Of the 363 participants, 355 completed both surveys. Outliers were identified using standardized residuals, with absolute values of 3 or higher flagged as extreme (Kline, 2015). Data from 10 students were excluded on this basis, resulting in a final analytic sample of 345 students: 144 elementary and 201 middle school students. As shown in Table 1, the sample comprised 193 males (55.9%) and 152 females (44.1%) students.

Table 1. Research participants

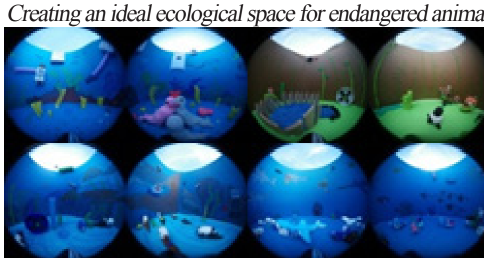
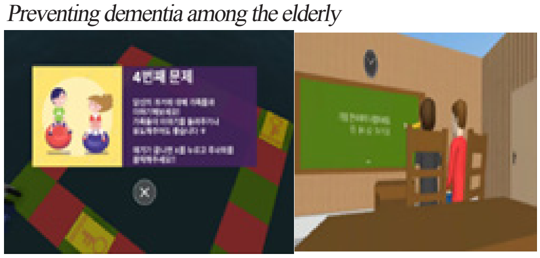
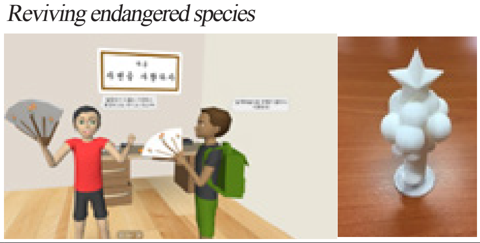
	Elementary school		Middle school		Total
	Group 1	Group 2	Group 3	Group 4	
Number(%)	78 (22.6%)	66 (19.1%)	96 (27.8%)	105 (30.4%)	345 (100.0%)
- Male	41	38	48	66	193
- Female	37	28	48	39	152
Grade	3^{rd}- 4^{th}	5^{th} - 6^{th}	1st-3rd	2nd	

Lesson Design and Implementation

The STEAM lessons were designed by the research team around two guiding principles. The first principle emphasized immersing students in authentic contexts where practical knowledge and skills are applied (Kelley & Knowles, 2016). To this end, socio-scientific issues (SSIs), including topics such as endangered species, climate change, and dementia in the elderly, were introduced as real-world problem-solving contexts. These SSIs provided meaningful scenarios that encouraged students to integrate disciplinary knowledge while engaging with socially relevant challenges.

The second principle centered on utilizing VR as a design tool. Rather than relying on traditional paper-based methods, VR enabled students to extend their design capacities by constructing virtual spaces that visually represented their understanding of SSIs and potential solutions. Using the CoSpaces (now Delightex) platform, students can utilize diverse materials, colors, and 3D objects, as well as integrate animation effects through coding. This approach offered a more expressive and dynamic medium for design, supporting creativity and problem-solving. Table 2 presents the specific socio-scientific issues addressed by each group and illustrates examples of the VR projects produced during the lessons.

Table 2. Socio-scientific issues and examples of VR work created by students

Group	Theme of socio-scientific issues and VR work	
Group 1	*Creating an ideal ecological space for endangered animals* 	Scientific standards and ideal habitats suitable for endangered animals such as great white sharks, long-lived turtles, and sea otters
Group 2	*Understanding how my friends' emotions change with the weather conditions* 	Cool sea and rain in an annoyingly hot summer. Sending a warm bus for a friend to go to school in the cold winter
Group 3	*Preventing dementia among the elderly* 	A matching game to train cognitive ability in elderly dementia patients and a classroom quiz activity to evoke memories of school days
Group 4	*Reviving endangered species* 	Promoting environmental protection by embedding the thorn lotus design in a fan and producing it through 3D printing

The learning activities were organized into a structured three-stage sequence (Figure 1). In the *Research & Creation* stage, students worked in groups to investigate their assigned socio-scientific issues and, drawing on their findings, used CoSpaces to design a VR project addressing the issue. In the *Experience & Discussion* stage, students used HMDs to explore both their own and other groups' VR creations. These experiences were accompanied by group discussions, where students exchanged reflections, ideas, and critiques of the VR artifacts. In the final stage, *Sharing & Feedback*, groups made formal presentations regarding their approach to solving the socio-scientific issues through the VR project. Presentations concluded with peer feedback, which shared insights and provided constructive suggestions for improvement. Within each group, students engaged with the same SSI topic and participated in VR-based learning activities across the three stages. The following sections offer detailed descriptions of the specific learning activities undertaken by each group.

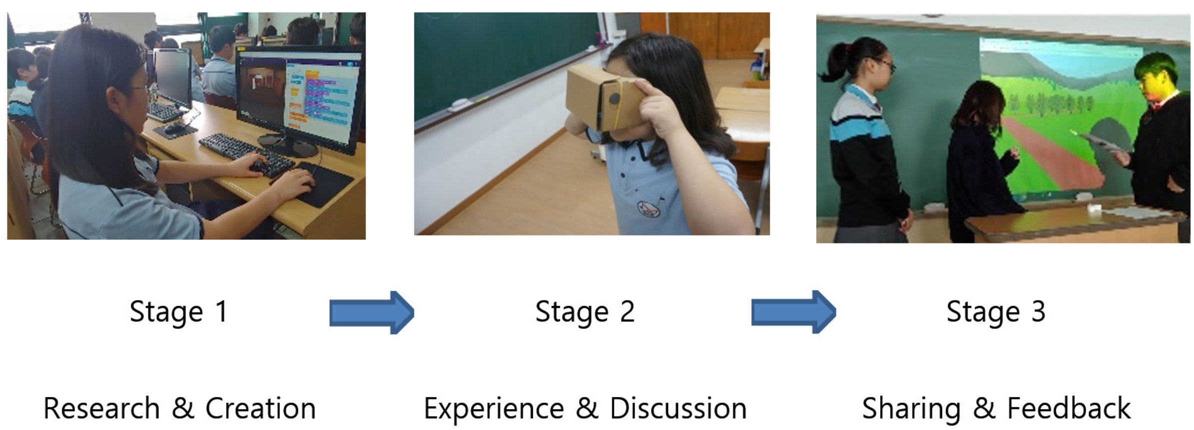


Fig. 1. Sequence of lesson activities

Group 1 (Elementary School, 3rd–4th Grades)

Under the theme "*Creating an Ideal Ecological Space for Endangered Animals*", students explored the ecological conditions necessary to support endangered species and designed ideal habitats using VR. In Stage 1, they researched the current status of endangered animals, causes of biodiversity loss, and conservation strategies. Based on their findings, they collaborated to design virtual ecological spaces tailored to the specific characteristics, lifestyles, and habitat needs of individual animals. Because of concerns about younger learners using VR, students combined traditional paper-based designs with digital tools to develop their projects. In Stage 2, they used Google Cardboard to experience other groups' VR creations and engaged in discussions on strategies for protecting endangered species. In Stage 3, groups presented their VR projects, explaining design rationale and conservation ideas, followed by peer feedback sessions to exchange insights and suggestions.

Group 2 (Elementary School, 5th–6th Grades)

The theme for Group 2 was "*Understanding How My Friends' Emotions Change with Weather Conditions*." Students examined the relationship between climate phenomena (e.g., heat waves, rainy seasons) and social issues linked to increased discomfort indices. Their task was to design VR artworks that could transform negative emotions caused by adverse weather into positive ones. In Stage 1, groups integrated science and moral education lessons to understand both the scientific principles of weather changes and their impact on emotional well-being. They then brainstormed ideas for VR artworks to improve emotional responses. In Stage 2, students learned to use the CoSpaces platform to create VR artifacts. In Stage 3, they finalized their VR creations and presented them in group sessions, concluding with peer feedback to refine and enhance their work.

Group 3 (Middle School, 1st-3rd Grades)

Group 3 focused on the theme "*Preventing Dementia Among the Elderly*," aimed at raising awareness of dementia as Korea faces an aging society. In Stage 1, students conducted research on the growing prevalence of dementia, investigating links between aging populations, scientific advances, and health challenges. They also collected real-life cases to develop empathy for dementia patients and their families. In Stage 2, drawing on their understanding of the nervous system and dementia treatment, students designed VR artifacts intended to provide both emotional and functional support to patients and caregivers. In Stage 3, they showcased their VR creations through group presentations, sharing innovative ideas on how technology can help address the challenges associated with dementia.

Group 4 (Middle School, 2nd Grade)

The theme for Group 4 was "*Reviving Endangered Species*." Students investigated the importance of biodiversity by exploring the status of endangered plants and conservation strategies. In Stage 1, the teacher introduced the Baobab tree as an entry point to spark interest and initiate discussions on biodiversity preservation. Students then conducted research and brainstormed ideas for VR artworks to raise awareness about plant conservation. In Stage 2, they learned to use the CoSpaces platform and 3D modeling techniques to design immersive VR spaces that demonstrated strategies for preserving endangered plants. In Stage 3, students finalized their VR designs and extended their work by using 3D printing to create physical models of their virtual creations. The lessons concluded with group discussions, where students reflected on the messages conveyed through their VR projects and shared insights on biodiversity conservation.

Measures

The primary objective of this study was to evaluate the impact of a design-oriented STEAM program incorporating VR on students' convergence competency. As illustrated in Figure 2, convergence competency in this study is defined across three dimensions: core skills, scientific inquiry, and design skills. These dimensions were selected to reflect the study's goal of fostering students' capacity to address complex real-world problems through scientific inquiry while also expressing creative solutions through VR design. The sub-components of each dimension were informed by prior research on STEAM education frameworks (e.g., Chen & Ding, 2023; Kim et al., 2012; So et al., 2019).

In this study, core skills refer to students' ability to communicate, collaborate, and apply convergence thinking in group work, enabling them to integrate and articulate interdisciplinary knowledge. Scientific inquiry emphasizes problem-solving processes in which students engage with socio-scientific issues through inquiry-based activities such as research, analysis, and reasoning (Reswara et al., 2024; Viehmann et al., 2024). Design skills focus on students' ability to generate ideas and visually express creative solutions to complex problems, using VR as a medium to represent and share their design.

To assess students' convergence competency, we developed an initial set of survey items based on a review of relevant studies. These items were refined through feedback from three STEAM education experts, resulting in a 27-item

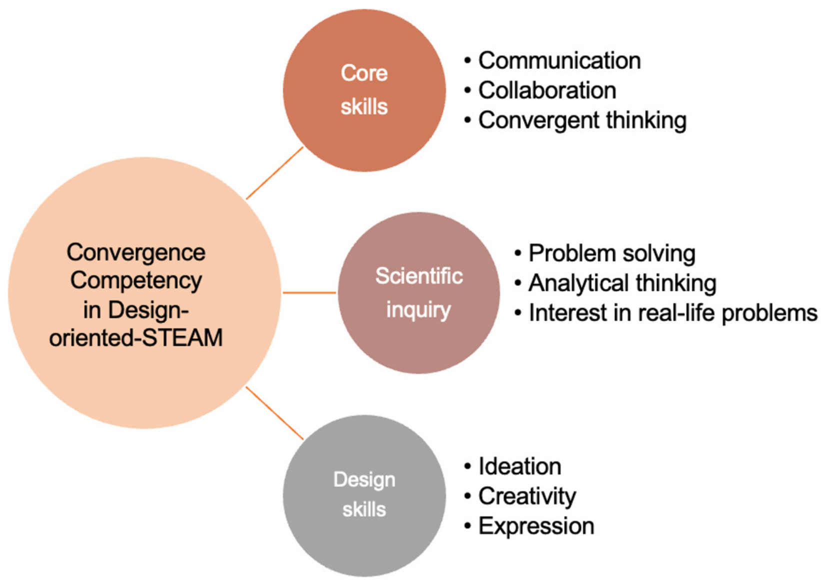


Fig. 2. Convergence competency in design-oriented STEAM education

instrument using a 5-point Likert scale, administered as both a pre- and post-survey. Exploratory factor analysis (EFA) of the pre-survey data yielded a final set of 13 items across three factors: core skills (5 items), scientific inquiry (4 items), and design skills (4 items). Reliability analysis indicated strong internal consistency, with Cronbach's alpha values of .798, .791, and .816, respectively, confirming the instrument's validity and reliability for measuring convergence competency. The final survey items and EFA results are presented in Table 3.

The post-survey included two additional 5-point Likert items designed to measure students' satisfaction and continuance intention in relation to the STEAM program. The first item, "Are you satisfied with your STEAM classes?" assessed overall satisfaction and provided insight into students' learning experiences. The second item, "Do you want to continue participating in STEAM classes in the future?" captured continuance intention, reflecting students' willingness to engage in future STEAM activities. Together, these items were intended to assess not only the immediate educational impact of the program but also its potential influence on students' sustained interest in design-oriented STEAM education.

Table 3. Exploratory factor analysis of the convergence competency instrument

Factors		1	2	3	Cronbach's *a*
Core skills					
1	When I come up with an idea, I connect various fields such as science, art, and society.	.753	.128	.129	.798
2	I can communicate and cooperate with those around me.	.603	-.100	-.161	
3	I can express my thoughts in a stable and harmonious way.	.595	-.038	-.052	
4	I can discuss the problem-solving process with others and work together.	.570	.144	-.059	
5	I have the ability to control if problems arise in conversations with those around me.	.554	.078	-.118	
Scientific inquiry					
6	I can design things that can be used in real life for their purpose.	-.055	.783	-.141	.791
7	I can come up with functional and convenient ideas in connection with real life.	-.032	.703	-.058	
8	I can discuss and explain ideas or solutions when the topic is given.	.204	.611	.088	
9	I can listen and understand ideas from others.	.276	.364	-.133	
Design skills					
10	I can express my ideas using appropriate materials.	-.041	.027	-.827	.816
11	Design ideas help solve real-life discomfort or problems.	.239	-.094	-.625	
12	I like to appreciate works in fine art or design.	.101	.119	-.621	
13	I usually come up with brilliant ideas that no one else thought of before.	-.015	.085	-.597	

** factor extraction method: principal axis factoring with direct oblimin rotation*

Data Collection and Analysis

Data were collected through pre- and post-surveys. The pre-survey was administered prior to the first STEAM class, while the post-survey was administered after the lessons and included additional items measuring student satisfaction and continuance intention. All data were analyzed using SPSS software.

The analysis proceeded in several steps. First, descriptive statistics (mean, standard deviation, skewness, kurtosis, and standardized residuals) were calculated to examine data trends and detect outliers. Based on standardized residual analysis, 10 outliers were excluded, resulting in a final sample of 345 students. Second, an exploratory factor analysis (EFA) was conducted on the pre-survey data to validate the measurement tool, using principal axis factor extraction for factor estimation and direct oblimin rotation for factor rotation. The EFA confirmed that 13 items were appropriate for measuring the three competency constructs. Third, paired-sample t-tests were conducted to assess significant differences between pre- and post-survey results across groups. Fourth, analysis of covariance (ANCOVA) was performed to examine gender differences, with pre-survey data used as covariates, post-survey data as dependent variables, and gender as the independent variable. This approach allowed for testing gender effects while controlling for initial competency levels. Finally, descriptive statistics and ANOVA were used to analyze satisfaction and continuance intention across groups. For all analyses, statistical significance was set at the .05 level.

Results

Overall Changes in Convergence Competency

Paired-sample t-tests were conducted to compare pre- and post-survey scores across the four groups (Table 4). Significant improvements were observed in all three competencies among Group 1 (3rd–4th graders), with the largest gain in scientific inquiry, which increased from 3.36 to 3.68 (t = -4.60, p < .05). In Group 2 (5th–6th graders), significant gains were found in core skills (t = -2.38, p < .05) and design skills (t = -2.91, p < .05), whereas no significant change was observed in scientific inquiry. Group 3 (7th–9th graders) demonstrated significant improvements across all three dimensions, with the most significant increase in core skills, rising from 2.95 to 3.21 (t = -3.81, p < .05). Group 4 (8th graders), which incorporated both VR and 3D printing, also showed significant gains in all three dimensions, including a significant improvement in scientific inquiry from 2.76 to 3.03 (t = -3.95, p < .05). Overall, the results indicate that participation in the VR-integrated STEAM program led to overall improvements in students' convergence competency across grade levels, except scientific inquiry in Group 2.

Table 4. Pre-survey and post-survey comparison in convergence competency

	Pre-survey	Post-survey	Pre-Post	SD	*t*	*p*
Group 1 (*n* = 78)						
Core skills	3.60	3.89	-.29	.55	-4.62*	.000
Scientific inquiry	3.36	3.68	-.32	.62	-4.60*	.000
Design skills	3.72	3.97	-.25	.59	-3.72*	.000
Group 2 (*n* = 66)						
Core skills	3.23	3.48	-.25	.85	-2.38*	.020
Scientific inquiry	2.97	3.05	-.08	.87	-.74	.458
Design skills	3.45	3.72	-.27	.74	-2.91*	005
Group 3 (*n* = 96)						
Core skills	2.95	3.21	-.26	.68	-3.81*	.000
Scientific inquiry	2.91	3.14	-.22	.64	-3.51*	.001
Design skills	3.32	3.51	-.20	.48	-4.03*	.000
Group 4 (*n* = 105)						
Core skills	2.92	3.10	-.18	.65	-2.86*	.005
Scientific inquiry	2.76	3.03	-.27	.70	-3.95*	.000
Design skills	3.18	3.38	-.20	.63	-3.25*	.002

Gender Differences in Convergence Competency

Table 5 presents the comparison of convergence competency by gender. Overall, female students demonstrated higher levels of core skills, whereas male students generally performed better in scientific inquiry. Across all four groups, female students consistently outperformed male students in core skills. In contrast, male students scored higher in scientific inquiry in most groups, except for Group 2, where female students obtained slightly higher post-survey scores (M = 3.11, SD = 0.76) compared to male students (M = 3.01, SD = 0.86). Patterns in design skills were more varied. In Groups 2 and 3, male students outperformed female students, while in Group 1, female students achieved higher scores, with a mean of 3.01 (SD = 0.86) across both surveys. In Group 4, male and female students performed at similar levels overall, although male students reported slightly higher post-survey scores (M = 3.43, SD = 0.82) than female students (M = 3.29, SD = 0.78).

To assess the statistical significance of these differences, ANCOVA was conducted using pre-survey scores as covariates to examine post-survey results by gender. The analysis revealed that, despite the observed differences in mean values, none of the gender differences were statistically significant across the four groups.

Table 5. Comparison by gender

Group 1		Male		Female			
		Mean	*SD*	*Mean*	*SD*	*F*	*p*
Core skills	Pre	3.48	.83	3.74	.78	.008	.930
	Post	3.80	.80	3.99	.84		
Scientific inquiry	Pre	3.58	.81	3.11	.71	.253	.930
	Post	3.89	.86	3.45	.85		
Design skills	Pre	3.70	.75	3.74	.66	1.613	.208
	Post	3.88	.80	4.07	.74		
Group 2		**Male**		**Female**			
		Mean	*SD*	*Mean*	*SD*	*F*	*p*
Core skills	Pre	3.14	376	3.35	.78	.262	.610
	Post	3.41	.79	3.58	.75		
Scientific inquiry	Pre	3.13	.78	2.76	.72	2.057	.156
	Post	3.01	.86	3.11	.76		
Design skills	Pre	3.53	.79	3.35	.70	.058	.810
	Post	3.74	.75	3.69	.73		
Group 3		**Male**		**Female**			
		Mean	*SD*	*Mean*	*SD*	*F*	*p*
Core skills	Pre	2.80	.79	3.10	.74	.003	.953
	Post	3.11	.68	3.31	.88		
Scientific inquiry	Pre	3.02	.91	2.79	.76	3.193	.077
	Post	3.34	.87	2.93	.93		
Design skills	Pre	3.47	.78	3.16	.75	1.030	.313
	Post	3.59	73	3.44	.80		
Group 4		**Male**		**Female**			
		Mean	*SD*	*Mean*	*SD*	*F*	*p*
Core skills	Pre	2.80	.84	3.13	.70	.009	.925
	Post	3.02	.80	3.25	.81		
Scientific inquiry	Pre	2.84	.86	2.63	.74	.265	.608
	Post	3.12	.95	2.88	.93		
Design skills	Pre	3.18	.72	3.19	.78	1.393	.241
	Post	3.43	.82	3.29	.78		

Learner Satisfaction and Continuance Intention

Table 6 presents the results of learner satisfaction with the VR-integrated, design-oriented STEAM program. Group 1 reported the highest satisfaction (M = 4.46), whereas Group 4 reported the lowest (M = 3.75). A one-way ANOVA confirmed significant differences among groups (F = 11.49, p < .001). Post-hoc comparisons showed that Group 1's satisfaction scores were significantly higher than those of Groups 2, 3, and 4, suggesting that younger students found the program more satisfying than their older counterparts.

Table 6. ANOVA and post-hoc analysis of student satisfaction

	Group 1	Group 2	Group 3	Group 4	F	*p*
Mean	4.46	4.00	3.81	3.75	11.49	.000

Post-hoc analysis

	Mean difference	*S.E*	*p*
Group 1 vs. Group 2	.46*	.15	.020
Group 1 vs. Group 3	.65*	.13	.000
Group 1 vs. Group 4	.71*	.13	.000
Group 2 vs. Group 3	.19	.14	.614
Group 2 vs. Group 4	.06	.12	.971
Group 3 vs. Group 4	.06	.12	.971

Regarding continuance intention, most groups expressed a strong willingness to continue participating in VR-based STEAM learning (Table 7). Group 4, however, reported a comparatively lower mean score (M = 3.55). A one-way ANOVA indicated no statistically significant differences across groups, suggesting that although 8th graders expressed relatively lower intention, their scores did not differ significantly from those of other groups.

Table 7. ANOVA results on continuance intention with STEAM classes

	Group 1	Group 2	Group 3	Group 4	*F*	*p*
Mean	4.12	4.03	4.04	3.55	1.71	.164

Discussion

The purpose of this study was to investigate the impact of a design-oriented STEAM program incorporating VR on fostering students' convergence competency. By engaging learners in designing and experiencing VR environments to address socio-scientific issues, the program aimed to promote interdisciplinary knowledge and problem-oriented learning. We hypothesized that VR, as an expressive and immersive medium, would enable students to create and present innovative solutions through dynamic and interactive experiences. The discussion revisits the research questions and highlights the key findings.

Regarding convergence competency, the results showed significant improvements across all groups, with the exception of scientific inquiry in Group 2. These findings align with previous research demonstrating the value of VR-based design activities in fostering interdisciplinary learning (Bae et al., 2018; Cho & Kim, 2019). Our study extends this line of work by confirming that VR not only enhances motivation (Chen & Hsu, 2020; Soto et al., 2020) but also enables students to act as creators rather than passive consumers. Unlike traditional paper-based or twodimensional approaches, VR offers an immersive environment where learners can visualize, explore, and present solutions in dynamic and meaningful ways. Using the CoSpaces platform, students both constructed 3D virtual worlds and experienced their peers' projects, thereby promoting creativity, critical thinking, and collaborative reflection. By positioning students simultaneously as creators and consumers of knowledge, the program facilitated deeper integration of disciplinary perspectives and strengthened their convergence competencies.

In terms of gender differences, the results indicated that female students tended to perform better in core skills, whereas male students showed higher performance in scientific inquiry. However, ANCOVA results confirmed that these differences were not statistically significant across groups, suggesting that neither developmental stage nor gender meaningfully influenced competency gains. This finding contrasts with prior studies that highlight persistent gender gaps in STEM participation and attitudes (Ma et al., 2022). Traditional STEM programs often emphasize technical tools and hands-on tasks that may appeal more to male students, while female students report lower engagement with such approaches. Our results suggest that embedding collaborative design tasks within VR-based STEAM education can help mitigate these disparities. By creating inclusive and interactive environments, design-oriented VR activities can support gender-equitable learning outcomes and reduce traditional gaps in engagement. The non-significant differences observed further suggest that gendered patterns in STEAM are not inevitable but shaped by pedagogical design and learning contexts. Positioning students as both creators and consumers of VR content may provide opportunities for all learners to draw on their strengths in collaboration, communication, or inquiry without reinforcing traditional stereotypes.

With respect to student satisfaction and continuance intention, the findings revealed consistently high levels of satisfaction across all groups. Group 1 (3rd–4th graders) reported significantly higher satisfaction than older students, suggesting that younger learners may be especially drawn to visually rich and creatively engaging activities. This aligns with prior research highlighting the affective benefits of VR and immersive technologies in sustaining motivation and engagement (Chen & Hsu, 2020; Shu & Huang, 2021). Students also expressed a strong intention to continue participating in STEAM education in similar formats. The higher satisfaction among younger learners may reflect the age-appropriate integration of paper-based and VR activities, as well as the novelty of VR experiences, which were new to many in this group. Future research should examine whether these positive perceptions persist over time as the novelty effect diminishes. Overall, the consistently high satisfaction and strong continuance intention underscore VR's potential to enhance student engagement and foster meaningful participation in STEAM learning

Some limitations of this study should be acknowledged. First, the STEAM program was implemented without a control group, which limits the generalizability of the findings to other contexts and subject areas. Given the nature of school-based research, groups were assigned different SSIs according to their curricula, making it impossible to establish a control group that did not use VR. Future studies should therefore employ controlled designs in comparable school settings and extend the investigation to additional disciplines. Second, the study measured only three aspects of convergence competency, excluding other skills integral to STEAM education. Learner-related variables such as prior knowledge and intrinsic motivation were also not assessed. Expanding the measurement framework to include a broader range of competencies and learner characteristics would provide a more comprehensive understanding of program effects. Third, the study did not evaluate the quality of students' VR projects. Incorporating assessments of project quality, student motivation, and collaboration in future work would yield a more holistic picture of how design-oriented STEAM education with VR influences learning. Moreover, the SSIs were not tied to specific regional contexts. Future research could incorporate more localized issues to enhance students' engagement and relevance. Finally, potential teacher effects were not examined in this study. In elementary schools, teachers typically integrate multiple subjects, while in middle schools, teachers specialize in distinct subject areas, which may influence lesson implementations. Although middle school teachers in this study collaborated to co-design and deliver the program, variations in instructional approaches may have shaped student outcomes. Future research should investigate the role of teacher expertise and instructional approaches in developing students' convergence competency.

Despite these limitations, the study contributes important insights into the potential of VR-based, design-oriented STEAM education. The findings demonstrate that engaging students in VR design activities to tackle socio-scientific issues in our society can strengthen convergence competencies, support inclusive learning environments, and sustain student interest in STEAM. By demonstrating how VR can serve as both an expressive medium and a collaborative learning space, this study extends current understandings of technology integration in STEAM education and offers valuable directions for future research.

Conclusion

This study examined whether integrating VR into design-oriented STEAM education could enhance students' convergence competency, focusing on core skills, scientific inquiry, design skills, gender differences, and learner satisfaction. The findings supported this hypothesis: students engaged in VR-integrated design activities demonstrated significant gains in convergence competency, expressed high levels of satisfaction, and showed strong intentions to continue STEAM learning, with no meaningful differences by gender. These results underscore VR's potential as both an expressive and collaborative tool that fosters inclusive and interdisciplinary learning. The study makes several contributions. First, it extends the literature on STEAM education by providing empirical evidence that design-oriented VR activities can strengthen convergence competencies beyond traditional methods. Second, it contributes to ongoing discussions of equity in STEM/STEAM by showing that immersive and collaborative design contexts can help reduce gender disparities in engagement and performance. Third, it highlights the role of VR not only as a motivational tool but also as a platform for students to act as creators, thereby deepening their integration of interdisciplinary knowledge. While the study has limitations, it offers a validated model of VR-enhanced, design-oriented STEAM education that can inform curriculum design and instructional practice. Future research should refine this model and examine its application across diverse educational settings to further explore its potential for advancing equitable and engaging STEAM learning.

Conflicts of Interest

The authors declared no conflicts of interest.

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