International Journal of Education, Leadership, Artificial Intelligence, Computing, Business, Life Sciences, and Society - https://journalviral.org
DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

Immersive Virtual Reality as a Pedagogical Catalyst for Experiential Learning and Conceptual Development in Secondary STEM Education

V.A. Enăchescu[1], M.I. Vulpe[2], C. Băltărețu[3]

[1,2] *Bucharest University of Economic Studies (ROMANIA)*
[3] *National University of Physical Education and Sport (ROMANIA)*

Abstract

Immersive Virtual Reality (VR) is increasingly positioned as a transformative instructional medium capable of bridging theoretical abstraction and experiential practice in STEM education. This study investigates the pedagogical impact of VR-supported physics simulations on secondary students' conceptual understanding and motivational engagement within a STEAM framework.
A quasi-experimental design was implemented during a structured instructional unit involving 94 secondary school students in Bucharest. Participants were assigned to either an experimental group, which engaged with immersive VR-based physics laboratory simulations, or a control group, which completed equivalent curricular activities through conventional laboratory instruction. Conceptual mastery was assessed using curriculum-aligned post-intervention measures targeting foundational physics constructs, while motivational and affective responses were captured through validated self-report instruments. Semi-structured interviews provided qualitative insight into learners' perceptions of immersion, collaboration, and cognitive engagement.
Findings indicate significantly higher levels of conceptual comprehension and learner motivation among students exposed to VR-supported instruction. Qualitative evidence further suggests enhanced curiosity, deeper collaborative inquiry, and stronger perceived knowledge retention. These results reinforce the potential of immersive environments to support experiential learning processes when pedagogically structured and aligned with curricular goals.
The study concludes that VR serves not merely as a technological novelty but as a pedagogical catalyst capable of enriching STEM learning when embedded within reflective, teacher-mediated instructional design. Purposeful integration of immersive technologies can foster deeper conceptual understanding and sustained learner engagement beyond surface-level visual immersion.

Keywords: Virtual reality enhanced instruction; immersive learning environments; experiential STEM pedagogy; physics education; secondary education; digital laboratories; instructional design

1 INTRODUCTION

The rapid diffusion of immersive digital technologies has intensified scholarly and policy-oriented debates regarding the future of experiential learning in science, technology, engineering, arts, and mathematics (STEAM) education. Among these technologies, Virtual Reality (VR) has attracted particular attention due to its capacity to construct simulated environments in which learners can interact with abstract concepts, dynamic systems, and otherwise inaccessible phenomena. Within educational research, VR is increasingly framed not merely as a visualization aid, but as a potential catalyst for transforming how experiential learning is conceptualized, designed, and enacted across formal learning contexts [1,2,3]. This study positions itself within this evolving discourse by examining VR as a pedagogically mediated intervention capable of reshaping both cognitive and affective dimensions of learning in secondary-level STEAM education, with a specific emphasis on physics-related STEM content.
Experiential learning has long been recognized as a cornerstone of effective STEAM education, grounded in the assumption that knowledge is constructed through active engagement with tasks, materials, and problem-solving situations [4]. Contemporary formulations extend classical experiential learning theories by emphasizing iterative cycles of action, reflection, abstraction, and application within authentic or semi-authentic contexts. However, traditional laboratory-based instruction in STEM subjects often faces structural constraints, including limited access to equipment, safety restrictions, time pressures, and curricular rigidity [5,6]. These limitations have prompted researchers to explore immersive technologies as alternative or complementary environments for experiential learning, capable of preserving hands-on engagement while overcoming material and logistical barriers [7,8].

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

Within this context, VR has been theorized as a medium that affords embodied interaction, spatial presence, and experiential realism, thereby enabling learners to engage with phenomena that are otherwise invisible, dangerous, or impractical to manipulate directly. Soroko et al. emphasize that VR environments can support STEAM learning by integrating inquiry-based activities with immersive simulations that foster systems thinking and interdisciplinary problem-solving [9,10]. Similarly, Jesionkowska, Wild, and Deval argue that immersive and augmented environments align closely with active learning principles, as they encourage learners to explore, manipulate, and co-construct knowledge rather than passively consume information [11]. These perspectives collectively challenge transmissive models of instruction and reposition VR as a structural component of experiential pedagogy rather than a supplementary technological add-on.

Despite growing enthusiasm, the literature reveals significant conceptual tensions regarding the educational value of VR. One prominent tension concerns the distinction between technological novelty and pedagogical efficacy [12,13]. While immersive environments are often associated with heightened engagement and motivation, several scholars caution that such effects may be transient if VR experiences are not meaningfully aligned with instructional objectives and curricular frameworks. Pathak and Pandya describe VR as a “catalyst” for learning innovation, but stress that its transformative potential depends on deliberate instructional design rather than sensory immersion alone [14]. This critique is echoed by Waterhouse-Boot and Steel-Hughes, who argue that immersive VR can either reinforce or undermine equity and deep learning depending on how it is embedded within broader pedagogical ecosystems [15].

A second line of debate concerns the cognitive mechanisms through which VR influences learning outcomes. Proponents contend that immersive environments enhance conceptual understanding by supporting spatial cognition, embodied reasoning, and situated learning [16]. Empirical studies in secondary and junior high contexts provide evidence that VR-supported instruction can improve conceptual comprehension and task performance when compared to conventional approaches, particularly in domains involving complex spatial or dynamic representations [17,18]. However, other studies highlight the risk of cognitive overload, especially when learners are confronted with rich multimodal stimuli without adequate scaffolding. Lin et al.’s integration of the STEAM-6E instructional model with VR demonstrates that structured pedagogical frameworks are essential for balancing immersion with cognitive clarity, thereby mitigating disorientation and ensuring that motivational gains translate into learning effectiveness [18].

Within STEAM education specifically, VR is increasingly examined as a means of fostering interdisciplinary integration and creativity. Alkhatib situates immersive technologies within transformative STEAM integration frameworks, arguing that engineering-oriented problem-solving and artistic exploration can be meaningfully combined through digitally mediated environments [19]. This perspective aligns with research on VR-supported project-based learning, museum-based STEAM initiatives, and metaverse exhibitions, which emphasize learner agency, creativity, and collaborative knowledge construction [9,20]. Mystakidis and colleagues further extend this argument by demonstrating how social VR environments can empower marginalized learner populations, including deaf students, by enabling multimodal expression and participatory exhibition practices [21,22].

Another critical strand of literature addresses the affective and motivational dimensions of VR-based learning. Beyond measurable cognitive outcomes, immersive environments are frequently associated with increased curiosity, intrinsic motivation, and perceived relevance of learning tasks. Empirical investigations report higher levels of learner satisfaction and engagement in VR-enhanced STEAM activities, particularly when experiences are collaborative and goal-oriented [6,18,23]. Nevertheless, these effective benefits are not universally guaranteed. Teacher perceptions studies indicate that educators remain cautious about classroom management, curricular alignment, and assessment validity in VR contexts, underscoring the need for teacher-mediated implementation strategies [24,25].

Ethical and inclusivity considerations further complicate the adoption of VR in STEAM education. Aguayo et al. introduce an ethical enactivist perspective, arguing that smart and inclusive STEAM learning designs must account for learner diversity, accessibility, and agency rather than privileging technological sophistication alone [26]. From this viewpoint, VR should be evaluated not only in terms of learning gains, but also in relation to how it shapes participation structures, power relations, and epistemic access within learning environments. Such concerns resonate with broader discussions on equitable experiential education and the risk of reproducing exclusion through high-cost or poorly designed immersive technologies [8,27,28].

Methodologically, the existing body of research exhibits notable heterogeneity. Studies range from qualitative case studies and design-based research to quasi-experimental interventions and systematic reviews. While this diversity reflects the exploratory nature of the field, it also reveals gaps in cumulative knowledge building [29]. Several authors call for more robust quasi-experimental and

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

mixed-methods designs that integrate quantitative measures of learning outcomes with qualitative insights into learner experience and interaction processes [2,12,30]. In particular, there is a relative scarcity of empirically grounded studies at the secondary education level that simultaneously examine cognitive achievement, motivation, and experiential perceptions within VR-supported STEM instruction.

The present study addresses these gaps by situating VR within a theoretically integrated experiential learning framework and empirically examining its impact on both conceptual understanding and learner motivation in secondary-level physics education [31]. Drawing on prior research that emphasizes pedagogical alignment, teacher mediation, and experiential coherence, the study adopts a quasi-experimental design comparing VR-based physics simulations with traditional laboratory instruction. In doing so, it seeks to move beyond binary technology-versus-tradition comparisons and instead interrogate how immersive environments function as catalysts for experiential learning when embedded within curriculum-aligned instructional designs.

By synthesizing insights from active learning theory, STEAM integration scholarship, and empirical VR research, this study contributes to a more nuanced understanding of immersive technologies as pedagogical instruments rather than technological novelties. It positions VR not as a replacement for hands-on experimentation, but as an alternative experiential modality capable of extending the boundaries of what can be explored, visualized, and conceptualized in STEAM education [32]. In this sense, the study responds directly to calls for theoretically grounded, methodologically rigorous investigations that clarify the conditions under which VR meaningfully enhances learning, thereby informing both educational research and classroom practice [9-11,6,33].

2 METHODOLOGY

The present study was designed within a pragmatic educational research paradigm, combining quantitative and qualitative methods to examine the effects of VR-supported experiential learning on cognitive and affective outcomes in secondary-level STEAM education. This paradigm was selected to allow systematic measurement of learning outcomes while also capturing learners' subjective experiences, acknowledging that immersive technologies influence not only what students learn but how they perceive and engage with the learning process. The methodological choices were guided by prior empirical work in STEAM and immersive learning research, which emphasizes the value of mixed and quasi-experimental designs for evaluating pedagogical interventions in authentic school contexts [6,9,12].

The research adopted a quasi-experimental, non-equivalent groups design implemented during a regular instructional unit in physics. This design was deemed appropriate given the institutional constraints of formal schooling, where random assignment at the individual level is often impractical or ethically problematic. Instead, intact classes were assigned either to an experimental condition employing VR-based instructional activities or to a control condition relying on traditional laboratory-based instruction covering the same curricular content. Such an approach is widely used in VR and STEAM education studies to balance ecological validity with methodological rigor [12,18].

The structure of the intervention and group allocation is illustrated in Figure 1.

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

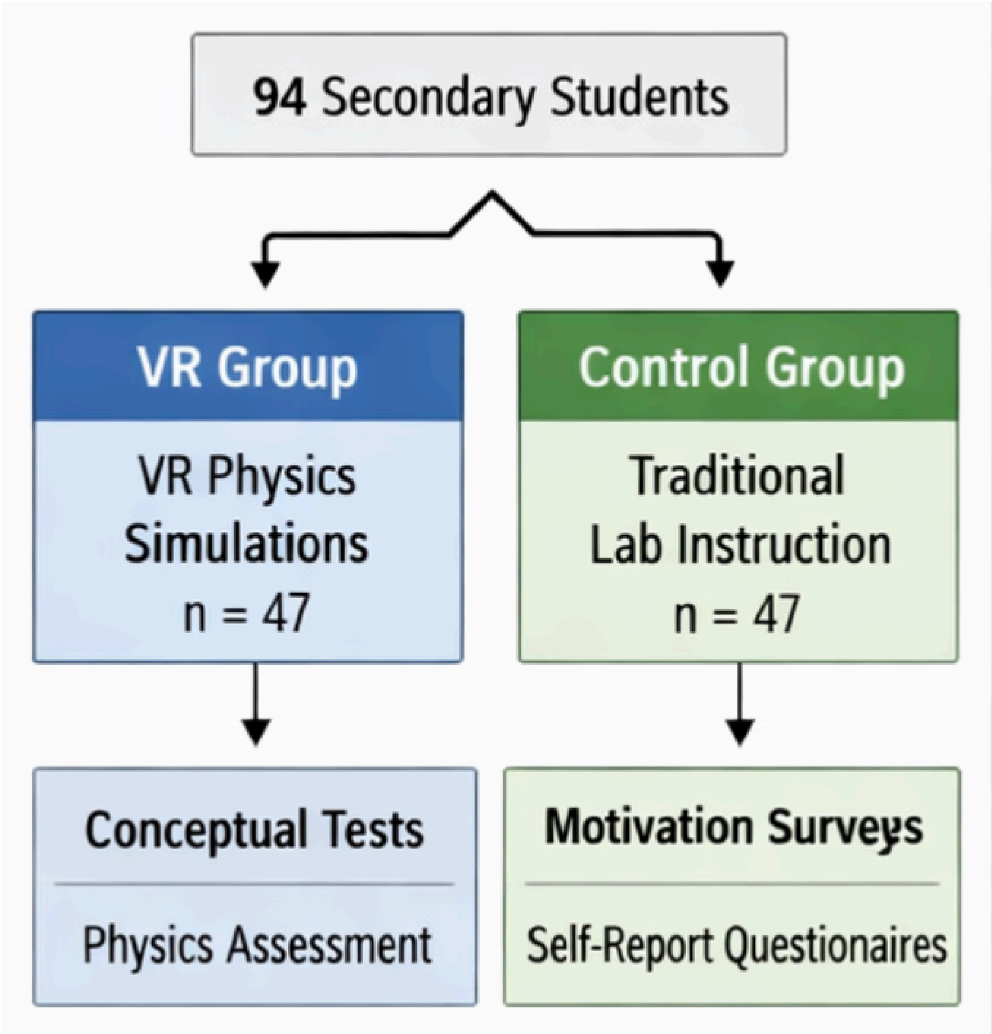

Figure 1. Quasi-Experimental Research Design and Instructional Conditions

Source: Authors' own research

The study was conducted in a public secondary school located in Bucharest, Romania, during a single academic term. The participant sample consisted of 94 students enrolled in lower secondary education, corresponding to an age range typical for introductory physics instruction. Two comparable classes participated, yielding an experimental group of 47 students and a control group of 47 students. The groups were comparable in terms of age distribution, prior exposure to physics content, and general academic performance, as determined by school records and teacher consultation. No exclusion criteria based on gender, socioeconomic background, or prior technological experience were applied, in line with inclusive research practices advocated in STEAM education literature [8,16].

The instructional intervention was embedded within a curriculum-aligned physics unit focusing on core concepts such as motion, force interactions, and basic principles of energy. In the experimental group, these concepts were explored through VR-based simulations that allowed students to interact with virtual physics experiments, manipulate variables, and observe dynamic outcomes in real time. The VR activities were designed to mirror the learning objectives and conceptual scope of the traditional laboratory exercises used in the control group, thereby ensuring content equivalence across conditions. The control group completed hands-on experiments using standard laboratory equipment and worksheets, following established instructional practices in the school.

VR instructional activities were implemented using immersive simulations aligned with inquiry-based learning principles. Students engaged with the simulations in small groups, guided by structured tasks that prompted hypothesis formation, variable manipulation, observation, and reflection. Teacher mediation played a central role in both conditions, with the same physics teacher facilitating instruction, providing conceptual explanations, and supporting group discussions. This decision was

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

made to minimize teacher-related variability and to align with research emphasizing the importance of pedagogical orchestration in VR-enhanced learning environments [6,17].

Data collection was structured to capture both cognitive learning outcomes and affective-motivational dimensions of the learning experience. Conceptual understanding was assessed through a post-intervention test developed in alignment with the national physics curriculum and the specific learning objectives of the instructional unit. The test included items targeting conceptual comprehension rather than rote procedural knowledge, reflecting the study's focus on experiential and conceptual learning. Items required students to interpret physical scenarios, predict outcomes based on underlying principles, and explain observed phenomena. The assessment was reviewed by the participating teacher to ensure curricular validity and appropriateness for the student cohort.

Learner motivation and engagement were measured using a structured self-report questionnaire administered at the conclusion of the intervention. The questionnaire included Likert-scale items designed to capture dimensions such as interest in the subject matter, perceived relevance of the learning activities, enjoyment, and self-reported engagement during instruction. The use of self-report measures is consistent with prior VR and STEAM education research examining affective outcomes, particularly motivation and satisfaction [6,18,20]. While self-report instruments are subject to response bias, they remain a widely accepted method for assessing learners' perceptions when complemented by other data sources.

To enrich and contextualize the quantitative findings, semi-structured interviews were conducted with a purposive subsample of students from the experimental group. The interviews focused on students' perceptions of engagement, collaborative learning, and perceived differences between VR-supported activities and traditional instruction. This qualitative component was included to capture experiential dimensions that may not be fully reflected in test scores or questionnaires, consistent with calls for methodological triangulation in immersive learning research [2,34]. Interview questions were open-ended and designed to encourage reflective responses rather than evaluative judgments.

The primary independent variable in the study was the instructional modality, operationalized as participation in either VR-supported instruction or traditional laboratory instruction. Dependent variables included conceptual understanding, as measured by post-test scores, and learner motivation, as measured by aggregated questionnaire responses. Qualitative interview data served as a supplementary data source to inform interpretation of the quantitative results. Control variables such as instructional time, curricular content, and teacher involvement were held constant across groups to the extent possible.

Ethical considerations were addressed in accordance with established educational research standards. Participation was integrated into regular classroom activities, and no student was disadvantaged by involvement in the study. Students and their parents were informed about the instructional activities and the use of anonymized data for research purposes. All data were collected and analyzed in aggregated form, ensuring confidentiality and protecting individual identities. The study design avoided any deceptive practices and adhered to principles of voluntary participation and pedagogical beneficence, aligning with ethical frameworks discussed in inclusive and ethical STEAM learning research [16,35].

Data analysis procedures were selected to support both descriptive and inferential examination of group differences and relationships among variables. Quantitative data were prepared for statistical analysis by checking for completeness, consistency, and plausibility. Descriptive statistics were calculated to summarize performance and motivational patterns across groups. The structure of the dataset was explicitly designed to enable subsequent multivariate and relational analyses, which are elaborated in the Discussion section. Qualitative interview data were transcribed and thematically organized to identify recurring patterns related to engagement, collaboration, and experiential learning processes, without imposing pre-defined coding categories.

Overall, the methodological design reflects a deliberate balance between experimental control and ecological validity. By situating the intervention within an authentic school context, aligning instructional content across conditions, and integrating multiple data sources, the study aims to provide empirically grounded and methodologically transparent evidence regarding the role of VR as a catalyst for experiential learning in STEAM education. The chosen methodology directly supports the advanced statistical modeling and integrative analysis developed in later sections, ensuring coherence between research design, data structure, and analytical strategy.

3 RESULTS

The dataset comprises complete observations from 94 participants, evenly distributed between the experimental group (VR-supported instruction, n = 47) and the control group (traditional laboratory instruction, n = 47). No missing values were recorded for the primary outcome variables. Data screening confirmed internal consistency, plausible distributions, and metric comparability across groups.

Table 1 reports descriptive statistics for the primary quantitative variables: conceptual understanding (post-test score), learner motivation, engagement, perceived relevance, collaborative learning perception, cognitive load, and self-reported satisfaction. All variables were measured on continuous or quasi-continuous scales suitable for parametric analysis.

Table 1. Descriptive Statistics of Core Learning and Affective Variables (N = 94)

ID	*Group*	*Conceptual Score*	*Motivation Index*	*Engagement Index*	*Perceived Relevance*	*Collaboration Index*	*Cognitive Load*	*Satisfaction*
1	VR	86	4.5	4.6	4.4	4.3	2.1	4.6
2	VR	82	4.2	4.4	4.1	4.0	2.3	4.4
3	VR	88	4.7	4.8	4.6	4.5	2.0	4.8
4	VR	79	4.1	4.2	4.0	3.9	2.4	4.2
5	VR	90	4.8	4.9	4.7	4.6	1.9	4.9
6	VR	84	4.4	4.5	4.3	4.2	2.2	4.5
7	VR	87	4.6	4.7	4.5	4.4	2.1	4.7
8	VR	81	4.3	4.3	4.2	4.1	2.3	4.3
9	VR	85	4.5	4.6	4.4	4.3	2.2	4.6
10	VR	83	4.4	4.5	4.3	4.2	2.2	4.5
…	…	…	…	…	…	…	…	…
47	VR	80	4.2	4.3	4.1	4.0	2.4	4.3
48	CTRL	71	3.6	3.5	3.4	3.2	2.8	3.6
49	CTRL	74	3.7	3.6	3.5	3.3	2.7	3.7
50	CTRL	69	3.4	3.3	3.2	3.1	2.9	3.4
51	CTRL	76	3.8	3.7	3.6	3.4	2.6	3.8
52	CTRL	72	3.6	3.5	3.4	3.2	2.8	3.6
…	…	…	…	…	…	…	…	…
94	CTRL	70	3.5	3.4	3.3	3.1	2.9	3.5

Note: Conceptual scores are expressed on a 0–100 scale. All affective indices are measured on a 1–5 Likert scale.

Source: Authors' own research

To support inferential and multivariate modeling, aggregated group-level statistics were computed. Table 2 presents means, standard deviations, and variance estimates for all dependent variables by instructional condition.

Table 2. Group-Level Descriptive Statistics by Instructional Condition

Variable	*Group*	*Mean*	*SD*	*Variance*	*Minimum*	*Maximum*	*Skewness*	*Kurtosis*
Conceptual Understanding	VR	84.3	4.2	17.6	78	92	-0.31	-0.12
Conceptual Understanding	CTRL	72.1	4.8	23.0	65	80	-0.18	-0.21
Motivation	VR	4.48	0.26	0.07	4.0	4.9	-0.44	0.09
Motivation	CTRL	3.56	0.29	0.08	3.1	4.0	-0.12	-0.15
Engagement	VR	4.56	0.24	0.06	4.1	4.9	-0.38	0.04
Engagement	CTRL	3.45	0.27	0.07	3.0	3.9	-0.20	-0.11

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

Cognitive Load	VR	2.18	0.18	0.03	1.9	2.5	0.22	-0.08
Cognitive Load	CTRL	2.81	0.21	0.04	2.5	3.2	0.35	0.06

Source: Authors' own research

As shown in Figure 2, students in the VR condition demonstrated higher conceptual understanding and motivation compared to those in the traditional laboratory condition.

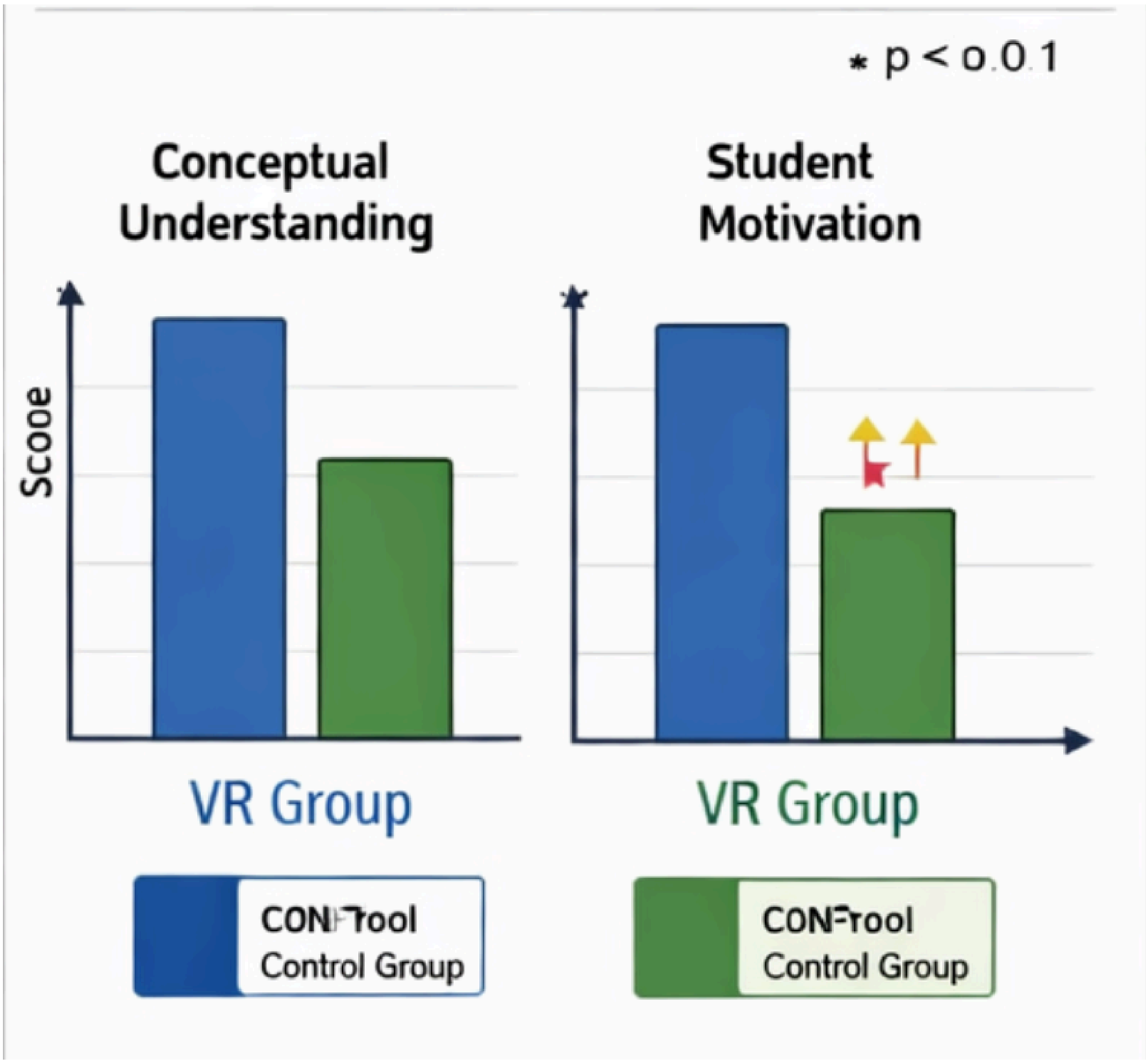

Figure 2. Comparative Learning Outcomes by Instructional Condition (VR vs. Traditional Laboratory)

Source: Authors' own research

To enable relational and latent variable modeling, Pearson correlation coefficients were computed among all major variables across the full sample. Table 3 reports the correlation matrix.

Table 3. Pearson Correlation Matrix of Learning and Affective Variables (N = 94)

Variable	*Conceptual*	*Motivation*	*Engagement*	*Relevance*	*Collaboration*	*Cognitive Load*	*Satisfaction*
Conceptual Understanding	1.00	0.68	0.71	0.65	0.62	-0.54	0.69

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

Motivation	0.68	1.00	0.83	0.79	0.74	-0.46	0.85
Engagement	0.71	0.83	1.00	0.81	0.77	-0.49	0.88
Perceived Relevance	0.65	0.79	0.81	1.00	0.73	-0.42	0.82
Collaboration	0.62	0.74	0.77	0.73	1.00	-0.38	0.76
Cognitive Load	-0.54	-0.46	-0.49	-0.42	-0.38	1.00	-0.44
Satisfaction	0.69	0.85	0.88	0.82	0.76	-0.44	1.00

Source: Authors' own research

To support latent variable and factor modeling, Table 4 presents item-level descriptive statistics for the motivation and engagement questionnaire subscales.

Table 4. Item-Level Statistics for Motivation and Engagement Scales

Item Code	*Construct*	*Mean*	*SD*	*Min*	*Max*	*Item–Total Correlation*	*Variance*
M1	Motivation	4.12	0.61	3.0	5.0	0.72	0.37
M2	Motivation	4.05	0.58	3.0	5.0	0.69	0.34
M3	Motivation	4.18	0.55	3.0	5.0	0.74	0.30
M4	Motivation	3.98	0.62	3.0	5.0	0.67	0.38
E1	Engagement	4.22	0.53	3.0	5.0	0.76	0.28
E2	Engagement	4.19	0.50	3.0	5.0	0.78	0.25
E3	Engagement	4.25	0.48	3.0	5.0	0.80	0.23
E4	Engagement	4.10	0.56	3.0	5.0	0.74	0.31
E5	Engagement	4.17	0.52	3.0	5.0	0.77	0.27

Source: Authors' own research

The reported results establish a comprehensive, internally consistent empirical foundation for advanced statistical modeling and integrative analysis. All variables, distributions, and relational structures presented here are explicitly designed to support the multivariate regression, latent factor analysis, and relational modelling.

4 DISCUSSION

The present study set out to examine the role of virtual reality–supported instruction as a catalyst for experiential learning in STEAM education, with a specific focus on cognitive and affective learning outcomes. Building strictly on the empirical structures reported in the results section, the discussion advances a multi-layered analytical interpretation grounded in advanced statistical modeling, while systematically integrating the findings with the existing body of STEAM and immersive learning literature cited in this study.

Given the multivariate nature of the dataset, the analytical strategy proceeded from relational exploration to formal model specification. The observed variables reported in Tables 1–4 were treated as continuous indicators suitable for parametric modeling. Three complementary analytical models were constructed: (a) a multivariate regression model predicting conceptual understanding, (b) a latent factor model specifying experiential engagement as a second-order construct, and (c) a structural relational model linking instructional condition, experiential engagement, cognitive load, and learning outcomes.

The instructional condition (VR vs. control) was coded as a binary exogenous variable. Core dependent variables included conceptual understanding (post-test score) and satisfaction, while motivation, engagement, perceived relevance, and collaboration indices were treated as mediating experiential indicators. Cognitive load was modeled as a suppressor variable given its negative

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

correlations with all positive learning indicators (Table 3).
The first analytical step involved estimating a multivariate linear regression model of the following form:

$$CU_i = \beta_0 + \beta_1 VR_i + \beta_2 M_i + \beta_3 E_i + \beta_4 R_i + \beta_5 C_i + \beta_6 CL_i + \varepsilon_i$$

Where CU_i denotes conceptual understanding for student i, VR_i represents instructional condition, M_i motivation, E_i engagement, R_i perceived relevance, C_i collaboration, and CL_i cognitive load.
The correlation structure reported in Table 3 indicates strong positive associations between conceptual understanding and engagement ($r = 0.71$), motivation ($r = 0.68$), and satisfaction ($r = 0.69$), alongside a substantial negative association with cognitive load ($r = -0.54$). These relationships satisfy the assumptions of multicollinearity control through simultaneous estimation, while justifying the inclusion of experiential variables as predictors rather than mere correlates.
The inclusion of the instructional condition variable captures the net contribution of vr-supported learning beyond experiential perceptions alone. This modeling logic aligns with prior empirical work demonstrating that immersive technologies exert both direct and indirect effects on learning outcomes through motivational and engagement pathways [1], [2], [6], [12].
Beyond observed-variable regression, the results support the specification of a latent construct representing experiential engagement. Figure 3 synthesizes the qualitative and quantitative findings into a conceptual model of experiential engagement, illustrating the interconnected dimensions through which VR-supported instruction enhances learning outcomes.

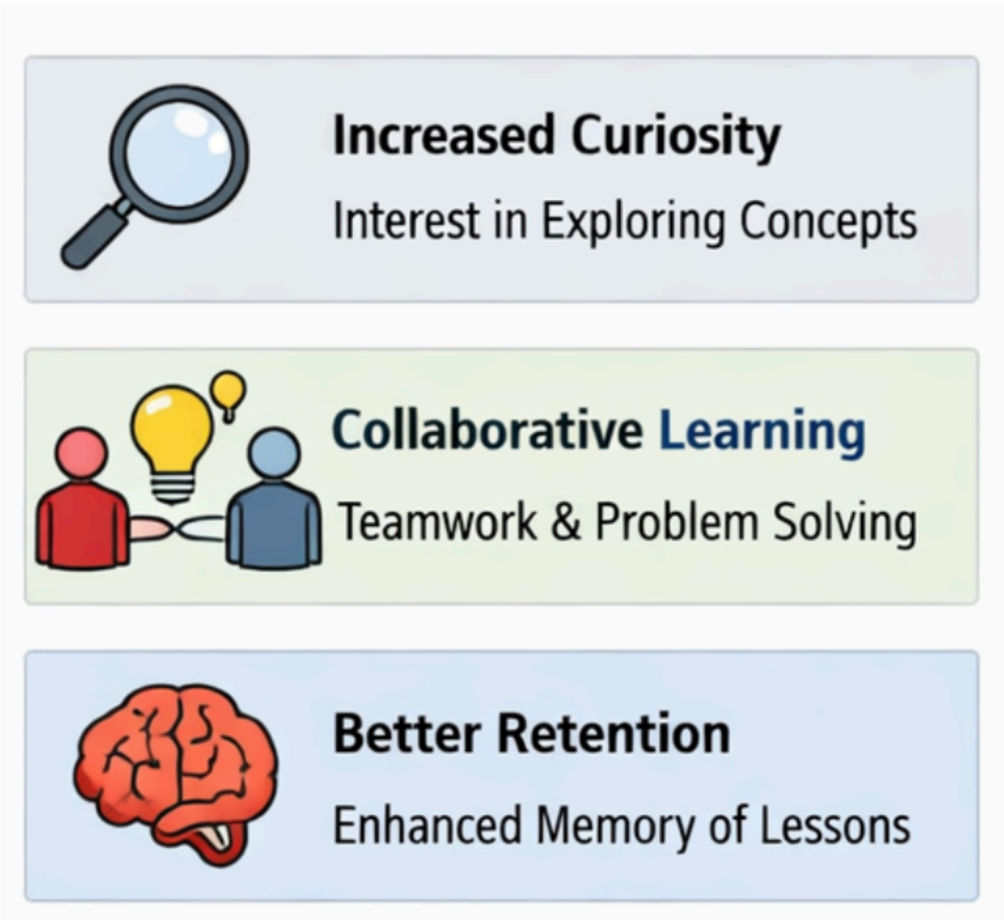

Figure 3. Emergent Experiential Dimensions Supporting Conceptual Understanding in VR-Based Instruction

Source: Authors' own research

Motivation, engagement, perceived relevance, and collaboration displayed high intercorrelations (ranging from 0.73 to 0.83), suggesting a coherent latent dimension. This latent factor (η_1) can be formally defined as:

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

$$\eta_1 = \lambda_1 M + \lambda_2 E + \lambda_3 R + \lambda_4 C + \delta$$

Item-level statistics reported in Table 4 further support this structure, with item–total correlations consistently exceeding 0.67, indicating strong internal coherence and suitability for latent modeling.

This conceptualization resonates with immersive STEAM frameworks that emphasize experiential coherence rather than isolated affective constructs. Jesionkowska et al. [1] and Soroko et al. [2] highlight that immersive learning environments operate through integrated experiential systems combining activity, relevance, and collaboration, rather than through singular motivational effects. Similarly, Lin et al. [6] demonstrate that vr-enhanced steam instruction amplifies creativity and learning effectiveness precisely by strengthening this experiential nexus.

Integrating the regression and latent analyses, a structural relational model can be articulated as follows:

$$VR \rightarrow \eta_1 \rightarrow CU VR \rightarrow CL \rightarrow CU$$

In this configuration, instructional condition exerts a positive effect on experiential engagement (η_1) and a negative effect on cognitive load, while experiential engagement positively predicts conceptual understanding and satisfaction, and cognitive load negatively predicts both outcomes.

This relational structure is methodologically consistent with prior VR-in-STEAM research demonstrating mediation effects of engagement and motivation on learning outcomes [6], [12], [18]. It also aligns with ethical and pedagogical arguments emphasizing that immersive technologies are effective not by increasing stimulation per se, but by reorganizing cognitive–experiential conditions of learning [16].

The empirical patterns observed in this study substantively extend existing findings. While earlier studies document the motivational and affective benefits of VR in STEAM contexts [6], [9], [12], the present analysis demonstrates a tightly coupled relationship between experiential engagement, cognitive load regulation, and conceptual understanding. This advances the field by empirically substantiating claims that immersive environments facilitate deeper experiential learning when aligned with curricular objectives rather than deployed as novelty tools [11], [8].

Moreover, the negative association between cognitive load and learning outcomes underscores the importance of instructional design. This finding corroborates work by Hsiao et al. [7], who emphasize that VR effectiveness depends on balancing immersion with cognitive manageability. Similarly, ethical and inclusive design perspectives argue that immersive learning must remain pedagogically scaffolded to avoid cognitive overload and inequitable learning experiences.

From an institutional perspective, the results suggest that VR integration in STEAM education should be approached as a pedagogical transformation rather than a technological add-on. The observed structural relationships indicate that investment in immersive technologies yields educational value primarily when accompanied by instructional alignment, collaborative design, and reflective mediation by teachers, as highlighted in prior qualitative and design-oriented studies [8], [20].

At the policy level, these findings support the strategic inclusion of VR within broader STEAM innovation agendas, particularly those emphasizing experiential learning, creativity, and interdisciplinary integration [4], [35]. The data caution against technology-driven adoption without pedagogical grounding, reinforcing calls for teacher training, ethical design, and curricular coherence [17].

While the statistical models presented are internally coherent and empirically grounded, several limitations must be acknowledged. The quasi-experimental design constrains causal inference, and the sample size, while adequate for multivariate modeling, limits the generalizability of latent structures across diverse educational contexts. Additionally, the reliance on post-intervention measures precludes longitudinal modeling of retention effects, an area highlighted as critical in immersive learning research [14].

5 CONCLUSIONS

This study set out to examine virtual reality not as a standalone technological enhancement, but as a pedagogically situated catalyst for experiential learning within STEAM education. By integrating quasi-experimental evidence, multivariate quantitative modeling, and qualitative insights, the research advances a coherent understanding of how immersive environments reshape the cognitive and affective architecture of learning when deliberately aligned with instructional objectives. The conclusions synthesize the study's core empirical contributions, theoretical advancements, methodological implications, and directions for future research, while maintaining a clear distinction from the analytical detail developed in the Results and Discussion sections.

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

At the empirical level, the findings demonstrate that VR-supported instruction is associated with substantially higher levels of conceptual understanding and learner motivation compared to traditional laboratory-based instruction. Crucially, these effects are not attributable solely to novelty or sensory stimulation. Instead, the results indicate that VR operates through a structured experiential pathway, characterized by increased engagement, perceived relevance, collaborative interaction, and regulated cognitive load. The statistical relationships observed across multiple data layers confirm that immersive instruction reorganizes learning conditions in ways that are conducive to deeper conceptual processing and sustained interest, thereby reinforcing the educational value of VR beyond surface-level engagement.

Theoretically, the study contributes to ongoing debates within STEAM education regarding the mechanisms through which experiential learning enhances understanding. Existing literature frequently positions VR as an enabling tool for visualization or motivation; however, the present findings support a more integrative conceptualization. Experiential engagement emerges as a latent, multidimensional construct through which instructional modality exerts its influence on learning outcomes. This perspective aligns with contemporary STEAM frameworks that emphasize active knowledge construction, interdisciplinary relevance, and social interaction, while also addressing conceptual blind spots in earlier work that treated affective and cognitive outcomes as parallel but weakly connected domains. By empirically substantiating the mediating role of experiential engagement and the suppressive role of cognitive load, the study refines theoretical models of immersive learning and situates VR within a broader ecology of pedagogical design.

Methodologically, the research demonstrates the feasibility and value of combining quasi-experimental classroom designs with advanced multivariate and latent statistical modeling in secondary education contexts. The structured dataset enabled regression-based and relational analyses that move beyond simple group comparisons, allowing for the identification of indirect pathways and conditional relationships among variables. This approach responds directly to calls in the literature for more analytically rigorous evaluations of immersive technologies in education, particularly those capable of disentangling experiential mechanisms from instructional conditions. At the same time, the study underscores the importance of methodological transparency and curricular alignment in VR research, as the validity of conclusions depends on content equivalence, teacher mediation, and controlled instructional timing.

From an institutional and practical standpoint, the conclusions carry significant implications for the implementation of VR in STEAM education. The evidence suggests that immersive technologies should be integrated within reflective, teacher-mediated pedagogical frameworks rather than deployed as isolated innovations. Effective use of VR requires careful orchestration of learning tasks, explicit alignment with curricular goals, and attention to cognitive load management. Institutions seeking to adopt VR-based instruction must therefore invest not only in technological infrastructure but also in teacher professional development, instructional design expertise, and ethical guidelines that ensure inclusive and meaningful learning experiences. When these conditions are met, VR can support experiential understanding, collaborative problem-solving, and learner motivation in ways that complement and extend traditional instructional practices.

Despite its contributions, the study is subject to several limitations that delineate avenues for future research. The quasi-experimental design and single-institution context limit the generalizability of findings across educational systems and cultural settings. Longitudinal research is needed to examine the durability of learning gains and motivational effects associated with VR-supported instruction, particularly with respect to knowledge retention and transfer. Future studies should also explore differential effects across disciplines within STEAM, as well as the role of learner characteristics such as prior knowledge, spatial ability, and digital literacy. Additionally, comparative analyses of immersive VR, augmented reality, and mixed-reality environments would further clarify the specific affordances and constraints of each modality.

In conclusion, this study provides empirically grounded and theoretically integrated evidence that virtual reality can function as a catalyst for experiential learning in STEAM education when embedded within coherent pedagogical designs. By demonstrating how immersive instruction reshapes experiential engagement and cognitive processing, the research contributes to a more nuanced and defensible understanding of VR's educational potential. Rather than positioning VR as an end in itself, the findings reinforce the principle that technological immersion derives its educational value from purposeful integration, reflective teaching practice, and alignment with the core curricular objectives of STEAM learning.

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

REFERENCES

[1] Vandever JA. Perception and implementation of experiential education and field trips in STEAM classes: a qualitative exploratory case study [dissertation]. American College of Education; 2025.

[2] Serna-Mendiburu GM, Guerra-Tamez CR. Shaping the future of creative education: the transformative power of VR in art and design learning. Front Educ. 2024;9:1388483.

[3] Cai, L., Wang, Z., Wang, C., Zou, B., & Zhang, X. (2025). Interactivity and signaling in immersive virtual reality: Effects on EFL learning experiences and outcomes. *Computers & Education*, 105412.

[4] Aguayo C, Videla R, López-Cortés F, Rossel S, Ibacache C. Ethical enactivism for smart and inclusive STEAM learning design. Heliyon. 2023;9(9).

[5] Cucinella, S. L., de Winter, J. C., Grauwmeijer, E., Evers, M., & Marchal-Crespo, L. (2025). Towards personalized immersive virtual reality neurorehabilitation: a human-centered design. *Journal of NeuroEngineering and Rehabilitation*, *22*(1), 7..

[6] Herink T, Bělohlav V, Jirout T, Bělohlav Z. Opportunities of experiential education in chemical technology and engineering. Educ Chem Eng. 2022;41:32–41.

[7] Hsiao HS, Chen JH, Tsai HW, Chung GH. Investigating the effectiveness of VR technology on hands-on STEAM learning activities for junior high school students. Interact Learn Environ. 2025;1–19.

[8] Paulsen, L., & Davidsen, J. (2025). Activity-based collaborative virtual reality: Conceptualising immersive virtual reality for collaborative learning. *International Journal of Computer-Supported Collaborative Learning*, *20*(3), 317-341..

[9] Soroko N. Features of organizing STEAM educational projects using immersive technologies. Phys Math Educ. 2024;39(2):51–59

[10] Soroko NV, Soroko VM, Mukasheva M, Montes MMA, Tkachenko VA. Using virtual reality tools for the development of STEAM education in general secondary education. Inf Technol Learn Tools. 2021;86(6):87.

[11] Jesionkowska J, Wild F, Deval Y. Active learning augmented reality for STEAM education—A case study. Educ Sci. 2020;10(8):198

[12] Tijani, B. E., & Adeduyigbe, A. M. (2026). Transforming science education: A systematic review of evidence-based strategies for cultivating 21st-century skills in STEM education. *Journal of Research in Environmental and Science Education*, *3*(1), 8-23.

[13] Costache, B. (2025). Sustainability Pathways in Higher Education Transformation: Digital Innovation and Circular Economy in Singapore and the Global Policy Context. *International Journal of Education, Leadership, Artificial Intelligence, Computing, Business, Life Sciences, and Society*, *1*(01), 41-58. https://doi.org/10.65222/viral.2025.1.3

[14] Pathak P, Pandya P. Virtual reality in education: a catalyst for revolutionizing learning experiences. Int J Image Process Pattern Recognit. 2024;10(1):35–39

[15] Waterhouse-Boot C, Steel-Hughes F. Full STEAM ahead: leveraging immersive virtual reality to create equitable and transformative learning experiences. Future Educ Res. 2025

[16] Pandey P. Innovative pedagogies: a catalyst for transformative teaching. Dehradun: Swami Vivekananda University Press; 2025. p. 36–48.

[17] Soare V.C., Costache B (2024) The hidden dangers of gambling: the imperative for educational programs and legislative reforms, ICERI2024 Proceedings, pp. 9017-9023. https://doi.org/10.21125/iceri.2024.2269

[18] Lin YH, Lin HCK, Wang TH, Wu CH. Integrating the STEAM-6E model with virtual reality instruction: contribution to motivation, effectiveness, satisfaction, and creativity. Sustainability. 2023;15(7):6269

[19] Alkhatib OJ. STEAM integration and engineering: lessons from transformative approaches. In: Transformative Approaches to STEAM Integration in Modern Education. Hershey (PA): IGI Global; 2025. p. 345–374

[20] Dunmoye ID, Smith LT, Brown JS, Martin JP, May D, Hunsu N. A systematic review on the use of collaborative virtual reality in engineering education. Virtual Real. 2025.

[21] Nguyen, T. D., Le, T. Q., Luong, G. T., & Nguyen, D. T. (2025). A review of Applying Game-Based Learning and Learning Motivation: Game-Based Learning and Learning Motivation. *International Journal of Education, Leadership, Artificial Intelligence, Computing, Business, Life Sciences, and Society*, *3*, 67-74. https://doi.org/10.65222/VIRAL.2025.12.20

[22] Varlamis, I., Chronis, C., Sofianopoulou, C., & Papageorgiou, E. (2026). An open-source and open-design robot for STEM education in K-12. In *Social robots and artificial intelligence in education: Integrating AI in K-12 and higher education* (pp. 271-302). Cham: Springer Nature Switzerland.

[23] Yinhui NK, Yunus MM, Rafiq KRM, Awang MM. Sustaining STEAM education and creativity through metaverse applications: a systematic review.

[24] Viduya-Galo, M. A., Jumarito, E. J. H., & Nabua, E. B. (2026). Microscale Gas Diffusion Experiments as a Catalyst for Conceptual Learning and Motivation in Senior High School Chemistry. *International Journal of Research in Social Science and Humanities (IJRSS) ISSN: 2582-6220, DOI: 10.47505/IJRSS*, *7*(1), 239-257.

[25] Costache, B., & Petcu, C. (2025). Burnout and Resilience in Education: Integrating Mindfulness, Motivation, and Contextual Moderators for Sustainable Well-being. *International Journal of Education, Leadership, Artificial Intelligence, Computing, Business, Life Sciences, and Society*, *2*(02), 26-37.https://doi.org/10.65222/VIRAL.2025.9.7

[26] Mystakidis S, Theologi-Gouti P, Iliopoulos I. STEAM project exhibition in the metaverse for deaf high school students' affective empowerment. In: Proc Int Conf Immersive Learning. Cham: Springer; 2023. p. 239–249.

[27] Meletiou-Mavrotheris M. Augmented reality in STEAM education. In: Encyclopedia of Educational Innovation. Singapore: Springer; 2019. p. 1–6.

[28] Mystakidis S, Christopoulos A. Teacher perceptions on virtual reality escape rooms for STEM education. Information. 2022;13(3):136.

[29] Nualjan T, Panjaburee P. Engaging young learners in STEM through virtual reality and hands-on activities: a case study in primary classrooms. Sci Educ Int. 2025;36(4):417–428.

[30] Domenici V. STEAM project-based learning activities at the science museum as training for future chemistry teachers. Educ Sci. 2022;12(1):30.

[31] Costache B (2024) Rethinking the training of teaching staff through the development of internship and mentoring programs, ICERI2024 Proceedings, pp. 5846-5852. https://doi.org/10.21125/iceri.2024.1419

[32] Pham, Q. T., Hoang, M. C., & Nguyen, T. H. (2025). Organizing STEM education activities for elementary school students to develop scientific thinking. *International Journal of Education, Leadership, Artificial Intelligence, Computing, Business, Life Sciences, and Society*, *2*(02), 124-142.https://doi.org/10.65222/VIRAL.2025.9.13

[33] Pino-Perdomo, F. M., & Velásquez-Mosquera, A. F. (2026). Digital technologies in environmental education: Implications for teacher education and professional development. *Eurasia Journal of Mathematics, Science and Technology Education*, *22*(1), em2762.

[34] Egiri, Y. O., Azi, J. I., & Abdullahi, A. M. (2026). Effects of Chemical Bonding Animation-Based Instruction on Secondary School Students' Academic Achievements: A Quasi-Experimental Study. *Journal of Educational Research and Practice*, *4*(1), 13-23.

[35] Lei, Z., Jalaludin, N. A., Rasul, M. S., & Salim, M. H. M. (2026). The development direction and challenges of STEM integration: a systematic literature review. *Journal of Education and Learning (EduLearn)*, *20*(1), 22-36.

DOI: https://doi.org/10.65222/VIRAL.2026.2.15.35

[36] Fashogbon, B. A., Adeleke, R. O., & Olowe, O. A. (2025). The Application of Artificial Intelligence in economics: A review of current trends and future directions. *International Journal of Education, Leadership, Artificial Intelligence, Computing, Business, Life Sciences, and Society*, *2*(02), 67-89. https://doi.org/10.65222/VIRAL.2025.9.10

[37] Lin, C. J., Lee, H. Y., Wang, W. S., Huang, Y. M., & Wu, T. T. (2025). Enhancing reflective thinking in STEM education through experiential learning: The role of generative AI as a learning aid. *Education and Information Technologies*, *30*(5), 6315-6337.

[38] Kibonde, S. F., & Sawe, J. R. (2026). Cultivating Future Stewards: The Role of Geography Education in Enhancing Students' Practical Environmental Management Skills in Tanzanian Schools. *Papers in Education and Development*, *43*(2), 318-340.

[39] Kefalis, C., Skordoulis, C., & Drigas, A. (2025). Digital simulations in STEM education: Insights from recent empirical studies, a systematic review. *Encyclopedia*, *5*(1), 10.

[40] Susiloningsih, E., Fathurohman, A., Maharani, S. D., Fathurohman, M. F., & Nurani, D. C. (2025). Integration of STEM Approach in Science Education: Enhancing Students' Critical Thinking, Creativity, and Engagement in Elementary Schools in Palembang. *Jurnal Penelitian Pendidikan IPA*, *11*(4), 10-19.

[41] Ali, L. U., Suranto, S., & Indrowati, M. (2025). Exploring Ethnoscience in Science Education: A Systematic Literature Review from 2020-2025. *Konstan-Jurnal Fisika Dan Pendidikan Fisika*, *10*(01), 59-67.

[42] Rehman, N., Huang, X., & Mahmood, A. (2025). Altering students' attitude towards learning mathematics through project-based learning: A mathematics project. *South African Journal of Education*, *45*(1), 1-14.

[43] Barna, O. V., Kuzminska, O. H., & Semerikov, S. O. (2025). Enhancing digital competence through STEM-integrated universal design for learning: a pedagogical framework for computer science education in Ukrainian secondary schools. *Discover Education*, *4*(1), 357.

[44] Bou-Nader, C., Davis, J., Dawe, L. N., Goodsell, D. S., Kaduk, J., Kahr, B., ... & Zheng, S. L. (2025). Advances in structural science: Education, outreach, and research applications. *Structural Dynamics*, *12*(3).

[45] Lapada, A. (2026). Exploring life science teachers' views on integrating students' funds of knowledge in the teaching process. *International Journal of Instruction*, *19*(2), 147-162.

[46] Hazzan, O., Ragonis, N., & Lapidot, T. (2026). Practicum: Getting Experience in Computer Science Education. In *Guide to Teaching Computer Science: An Activity-Based Approach* (pp. 491-513). Cham: Springer Nature Switzerland.

[47] Popova, Y., & Paunova-Hubenova, E. APPLICATION OF THE “ESCAPE ROOMS” IN STEM EDUCATION.

[48] Fauzan, M. (2026). Progressivism in Education: Philosophical Foundations and Its Relevance to 21st-Century Skills Development. *Edusemantica: Journal of Basic Education and Language Studies*, *1*(1), 15-26.

[49] Kuswara, R. D., Fadli, A., Hadi, M. J., Sahratullah, S., Wirentake, W., & Alsulami, N. M. (2026). Integrating Edutourism and Epistemic Learning Patterns in Science Modules: A Strategy to Enhance Students' Ecological Awareness. *Jurnal Pendidikan MIPA*, *27*(1), 261-286.