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VIRTUAL REALITY-BASED DEVELOPMENT OF STUDENTS' SYSTEMS THINKING IN PHYSICS EDUCATION: A PEDAGOGICAL MODEL AND EXPERIMENTAL STUDY

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Abstract: Systems thinking is increasingly important in physics education because understanding complex physical phenomena requires students to identify system elements, establish relationships among variables, analyze causal mechanisms, construct models, predict changes, and integrate observations into coherent explanations. This study evaluated a virtual reality (VR)-supported pedagogical methodology designed to develop undergraduate students' systems thinking in physics. A quasi-experimental pre-test/post-test design involved 299 students from three higher education institutions in Uzbekistan, with 150 students in the experimental group and 149 in the control group. The methodology integrated the VRphyzics.uz educational platform with virtual experimentation, interactive modeling, systemic analysis, prediction, and reflective activities. Systems thinking was operationalized through four interconnected components: technological-analytical, constructive-modeling, innovative-transformational, and reflective-integrative. Baseline distributions did not differ significantly between groups, $\chi^2(2) = 0.095$, $p = .954$. Following the intervention, the transformative level in the experimental group increased from 12.0% to 26.7%, the integrative level from 27.3% to 45.3%, and the analytical level decreased from 60.7% to 28.0%. Post-test distributions differed significantly between groups, $\chi^2(2) = 21.20$, $p < .001$. The experimental group also obtained a higher integral score ($M = 1.987$, $SD = 0.742$) than the control group ($M = 1.604$, $SD = 0.724$), $t(297) = 4.51$, $p < .001$, Cohen's $d = 0.52$. The findings indicate that VR can support systems-thinking development when embedded in structured analytical, modeling, transformational, and reflective learning activities.

Keywords: virtual reality; systems thinking; physics education; computational modeling; VRphyzics; higher education; virtual experiment

1. Introduction

Systems thinking has become increasingly important in science education because many scientific phenomena cannot be adequately understood by examining individual objects or variables in isolation. Learners must identify the components of a system, recognize relationships among those components, interpret causal mechanisms, understand dynamic behavior, construct models, and integrate separate observations into a coherent representation of the system as a whole.

These abilities are particularly important in physics. Electrical circuits, electromagnetic fields, oscillatory processes, thermodynamic systems, and optical phenomena consist of interacting variables whose behavior cannot always be understood through isolated factual or mathematical knowledge. A student may correctly recall a physical law while experiencing difficulty explaining how the corresponding system behaves when one or more parameters change. Physics education therefore

requires learners not only to acquire conceptual and mathematical knowledge but also to reason about physical phenomena as interconnected systems.

Systems-thinking research in science education has established that the construct involves increasingly complex cognitive operations. Ben-Zvi Assaraf and Orion (2005) described systems-thinking development through abilities ranging from identifying system components and relationships to organizing these relationships, recognizing dynamic processes, and understanding hidden dimensions of systems. Sweeney and Sterman (2007) likewise demonstrated persistent difficulties in intuitive reasoning about dynamic systems, while Davis et al. (2018) emphasized the need to assess complex reasoning through ill-structured problems.

Digital technologies provide new opportunities for representing and manipulating complex physical systems. Virtual reality is particularly relevant because it can enable learners to interact with processes that are difficult to observe or manipulate directly. Reviews of immersive VR nevertheless show that immersion alone does not guarantee learning; outcomes depend on pedagogical design, learner interaction, assessment, and the alignment between technological affordances and instructional objectives (Radianti et al., 2020; Hamilton et al., 2021; Makransky & Petersen, 2021).

Recent physics-specific evidence reinforces this point. Vidak et al. (2026) reviewed immersive VR implementation in physics education and identified both substantial opportunities for active interaction with physical representations and continuing challenges in instructional design and research methodology. In parallel, Sun et al. (2026) synthesized 62 effect sizes from 25 studies and reported a positive overall effect of computational modeling on systems thinking ($g = 0.470$), with the largest effect for applying and evaluating systems.

The present study addresses this intersection by integrating VR-supported physics learning with systems-thinking development. Rather than treating VR primarily as a visualization technology, the methodology organizes learning around four interconnected components: technological-analytical, constructive-modeling, innovative-transformational, and reflective-integrative. The VRphyzics.uz platform provides the technological environment in which these activities can be implemented through virtual experiments, simulations, interactive models, and diagnostic tasks.

The study addressed four research questions: (RQ1) Are the experimental and control groups comparable in their systems-thinking levels before implementation of the VR-supported methodology? (RQ2) How do analytical, integrative, and transformative systems-thinking levels change following the intervention? (RQ3) Is there a statistically significant post-intervention difference between the experimental and control groups? (RQ4) How can VRphyzics.uz function as an instructional and diagnostic environment for systems-oriented physics learning? It was hypothesized that students participating in the structured VR-supported methodology would demonstrate a greater transition from analytical reasoning toward integrative and transformative systems-thinking levels than students receiving conventional instruction.

2. Materials and Methods

The study employed a quasi-experimental pre-test/post-test design. The pedagogical experiment involved 299 undergraduate students studying physics and astronomy at Jizzakh State Pedagogical University, Bukhara State Pedagogical Institute, and Navoi State University. The experimental group consisted of 150 students and the control group of 149 students. The intervention focused primarily on electricity and magnetism. The experimental group studied relevant physics content using the

developed VR-supported methodology, while the control group studied corresponding content through conventional instructional practices.

Systems thinking was operationalized through four interconnected components. The technological-analytical component represented students' ability to identify essential elements and parameters of a physical system and analyze their functions using digital and virtual tools. The constructive-modeling component represented the ability to establish relationships among elements and construct or interpret physical, graphical, mathematical, and virtual models. The innovative-transformational component involved modifying system parameters, generating alternative configurations, predicting outcomes, and considering alternative solutions. The reflective-integrative component involved evaluating experimental and modeling results, identifying inconsistencies, connecting physical concepts, and integrating separate observations into a holistic interpretation.

The pedagogical experiment consisted of diagnostic, formative, and control-analytical stages. During the formative stage, learning activities progressed through motivational-orientational, cognitive-analytical, practical-project, integrative-modeling, innovative-creative, and reflective-evaluative processes. Students therefore moved from initial observation and identification of system elements toward analysis, modeling, transformation, prediction, and reflection.

The experimental environment incorporated VRphyzics.uz, virtual experiments, interactive simulations, three-dimensional models, and virtual laboratories. These resources were combined with VEEM, the Iceberg method, Systemic Inversion, and Systemic Analysis. The Iceberg method encouraged movement from directly observable manifestations toward underlying mechanisms and causal relationships. Systemic Inversion encouraged reverse reasoning and exploration of alternative configurations. Systemic Analysis required students to synthesize system elements, relationships, interactions, and experimental findings into an integrated explanation.

VRphyzics.uz was additionally used as a diagnostic environment. Its task bank includes systems-oriented physics problems requiring learners to identify system elements, establish relationships, analyze causal mechanisms, predict effects of parameter changes, and interpret physical phenomena holistically. The platform automatically records test results, percentage scores, assessment type, and completion time. Platform-generated records were treated as supplementary operational data rather than as an extension of the experimental sample because the raw database contains repeated attempts and technical verification records.

Overall systems-thinking development was classified into analytical, integrative, and transformative levels. For statistical analysis, these levels were coded as 1, 2, and 3, respectively. Pearson's chi-square test was used to compare categorical distributions between groups. Integral level scores were compared using an independent-samples Student's t-test, and the standardized between-group difference was estimated with Cohen's d. Statistical significance was evaluated at $\alpha = .05$.

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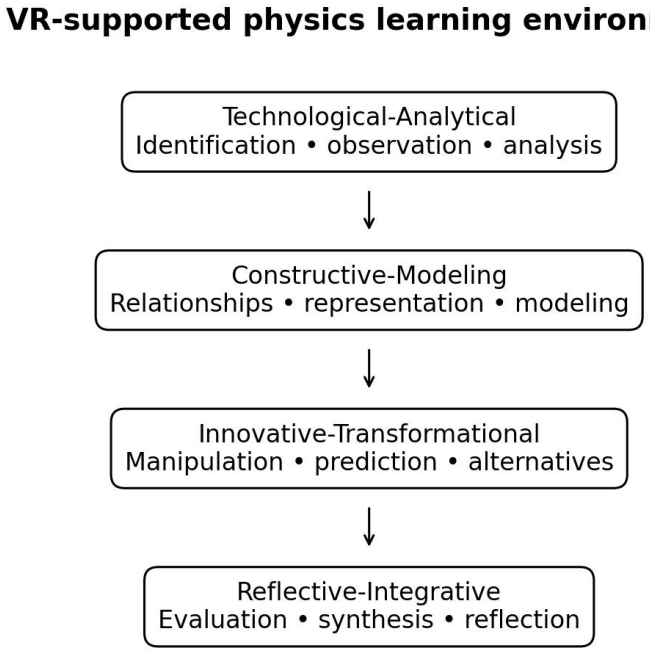

Figure 1. Conceptual structure of the VR-supported systems-thinking methodology.

3. Results

Before the intervention, the experimental and control groups demonstrated nearly identical systems-thinking distributions. In the experimental group, 18 students (12.0%) were classified at the transformative level, 41 (27.3%) at the integrative level, and 91 (60.7%) at the analytical level. In the control group, the corresponding frequencies were 17 (11.4%), 43 (28.9%), and 89 (59.7%). Pearson's chi-square test showed no statistically significant baseline difference, $\chi^2(2) = 0.095$, $p = .954$.

Systems-thinking level	Experimental pre-test n (%)	Experimental post-test n (%)	Control pre-test n (%)	Control post-test n (%)
Transformative	18 (12.0)	40 (26.7)	17 (11.4)	21 (14.1)
Integrative	41 (27.3)	68 (45.3)	43 (28.9)	48 (32.2)
Analytical	91 (60.7)	42 (28.0)	89 (59.7)	80 (53.7)
Total	150 (100)	150 (100)	149 (100)	149 (100)

Following the intervention, the transformative level in the experimental group increased from 12.0% to 26.7%, the integrative level from 27.3% to 45.3%, and the analytical level decreased from 60.7% to 28.0%. Changes in the control group were considerably smaller. The post-test distributions differed significantly between groups, $\chi^2(2) = 21.20$, $p < .001$.

When the three developmental levels were coded as 1, 2, and 3, the experimental group obtained a post-test mean integral score of M = 1.987 (SD = 0.742), compared with M = 1.604 (SD = 0.724) in the control group. The independent-samples analysis indicated a statistically significant difference, $t(297) = 4.51$, $p < .001$. The standardized difference was Cohen's $d = 0.52$, indicating a moderate between-group effect.

Indicator	Experimental group	Control group
n	150	149
Mean integral score	1.987	1.604
Standard deviation	0.742	0.724
Integral indicator	66.2%	53.5%
Transformative + integrative	72.0%	46.3%

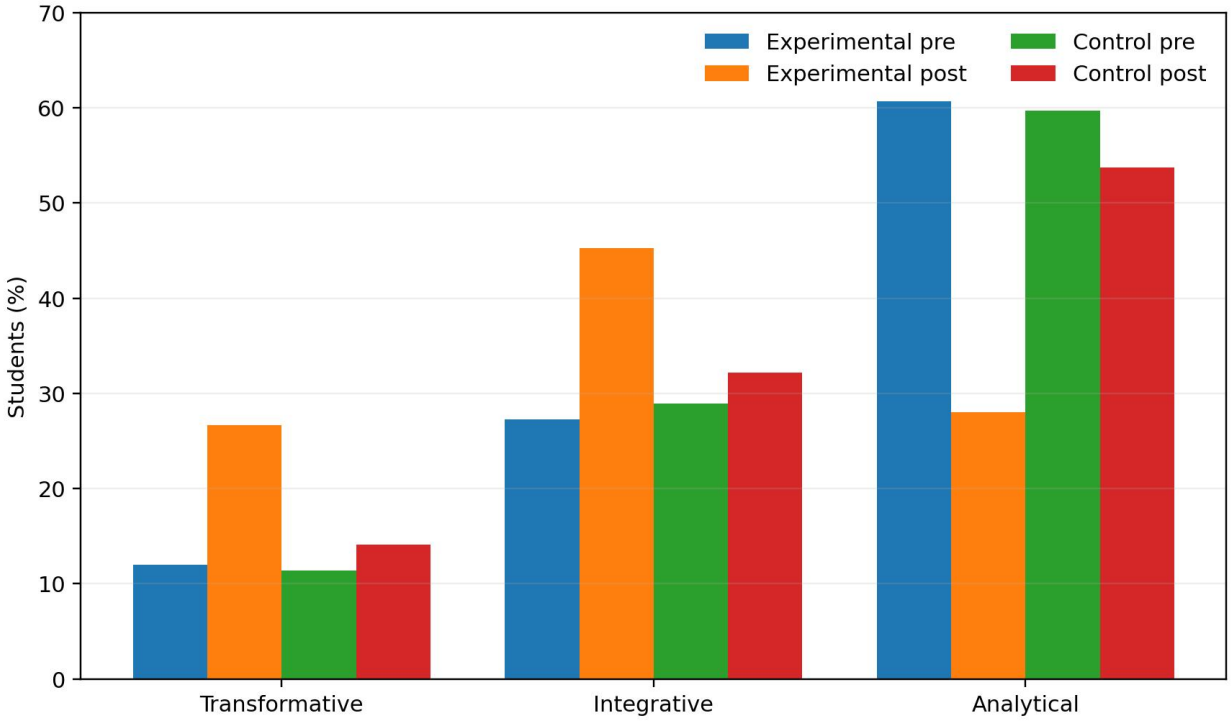

Figure 2. Pre-test and post-test distributions of systems-thinking levels.

The VRphyzics.uz operational database provided supplementary evidence concerning platform use. During 14–18 September 2026, the database contained 81 recorded assessment entries, including 79 VR-test attempts and two image-based test attempts. The VR-test records represented 73 unique anonymized identifiers. After retaining the latest VR-test attempt for each unique identifier, the mean score was 85.1%, the median was 87%, and scores ranged from 13% to 100%. These descriptive platform statistics were not included in the inferential evaluation because the log dataset did not contain sufficient information for matching records to experimental/control status and institution.

Platform indicator	Value
Recorded assessments	81
VR-test attempts	79
Image-based attempts	2
Unique VR-test identifiers	73
Mean score after deduplication	85.1%
Median	87%
Minimum	13%
Maximum	100%

4. Discussion

The findings indicate that the VR-supported pedagogical methodology was associated with a substantial development of students' systems thinking. The experimental and control groups were statistically comparable before implementation, whereas significant differences emerged after the intervention. The main educational change was a redistribution from predominantly analytical reasoning toward integrative and transformative reasoning: 72.0% of experimental-group students reached one of the two higher levels at post-test, compared with 46.3% of control-group students.

This pattern is consistent with a developmental interpretation of systems thinking. Identification of system elements is an important starting point, but higher-level systems reasoning requires learners to reconstruct relationships, predict dynamic behavior, evaluate alternative configurations, and integrate observations into coherent explanations. The four-component framework operationalizes this progression for physics through analysis, modeling, transformation, and reflection.

Computational modeling provides a relevant comparison. Sun et al. (2026) reported an overall positive effect of computational modeling on systems thinking ($g = 0.470$), with a larger effect for applying and evaluating systems. The effect observed in the present study ($d = 0.52$) is broadly compatible in magnitude, although direct equivalence should not be assumed because interventions, populations, instruments, and designs differ. The theoretical relationship is nevertheless meaningful: computational and virtual models allow learners to externalize relationships, manipulate variables, observe consequences, and compare predicted and actual behavior.

The findings are also consistent with physics-specific VR research. Vidak et al. (2026) reviewed 34 immersive-VR studies in physics education and highlighted opportunities created by active interaction with physical representations while emphasizing continuing implementation and design challenges. The present study extends this literature by focusing specifically on systems thinking as an outcome and by treating VR as part of an integrated instructional methodology rather than an isolated medium.

This distinction is central. An electromagnetic-induction simulation becomes a systems-thinking environment only when students identify relevant elements, establish causal relationships, predict effects of parameter changes, test predictions, and integrate observations into an explanatory model.

Likewise, an electrical-circuit activity can progress from calculating current to predicting how changes in resistance affect the whole system and redesigning the configuration to achieve a specified outcome.

The moderate effect size is important because statistical significance alone is influenced by sample size. Reporting χ^2, the t-test, and Cohen's d provides complementary evidence concerning distributional change, mean-level difference, and standardized magnitude. At the same time, the quasi-experimental design does not establish that VR alone caused the observed difference. The intervention combined VR, virtual experimentation, modeling, systemic-analysis methods, prediction, alternative-solution generation, and reflection.

The platform database also illustrates a methodological issue common to digital learning research: an assessment attempt is not necessarily equivalent to an independent participant. Repeated attempts and technical verification records must be distinguished before inferential analysis. Future versions of VRphyzics.uz should therefore assign anonymized longitudinal identifiers, distinguish practice from formal diagnostic attempts, label pre-test and post-test sessions, and associate items with the four systems-thinking components.

Several limitations should be acknowledged. Intact educational groups were used rather than individual random assignment. The intervention contained multiple pedagogical elements, preventing isolation of the contribution of each element. The three-level classification simplifies a multidimensional construct. Platform analytics were supplementary rather than longitudinal experimental data. Finally, replication across physics topics, institutions, countries, and educational levels is needed before broader generalizations are made.

5. Conclusion

This study investigated the development of undergraduate students' systems thinking through a structured VR-supported methodology in physics education. The framework integrated technological-analytical, constructive-modeling, innovative-transformational, and reflective-integrative components with virtual experimentation, interactive modeling, systems analysis, prediction, alternative solution generation, and reflective evaluation.

The quasi-experimental study involved 299 students. Baseline systems-thinking distributions did not differ significantly between the experimental and control groups, $\chi^2(2) = 0.095$, $p = .954$. Following the intervention, a statistically significant difference emerged, $\chi^2(2) = 21.20$, $p < .001$. The experimental group obtained $M = 1.987$ ($SD = 0.742$), compared with $M = 1.604$ ($SD = 0.724$) in the control group, $t(297) = 4.51$, $p < .001$, Cohen's $d = 0.52$.

These findings support the use of VR as part of a pedagogically structured systems-thinking environment rather than as an isolated visualization technology. The educational contribution of VRphyzics.uz lies in enabling students to progress through interconnected cognitive activities involving identification, analysis, modeling, manipulation, prediction, evaluation, and reflection. Future research should examine individual components of the model, retention and transfer, and anonymized longitudinal learning analytics.

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