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Enhancing Systems Thinking in Elementary Science Education: A STEM-Based Approach for Fourth-Grade Learners

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Abstract

The present study investigates the impact of STEM-based activities on the systems thinking skills of fourth-grade students. The research aims to determine whether STEM-integrated learning enhances students' ability to analyze, synthesize, recognize relationships, and develop a holistic understanding of scientific concepts. The study employed a quasi-experimental design with a sample of 66 fourth-grade students from the Muscat Governorate, Oman, divided into two groups: a control group that received traditional instruction and an experimental group that engaged in STEM-based activities. A pre-test and post-test measuring system for thinking skills was administered to both groups. Data were analyzed using an independent samples t-test to assess differences in post-test scores between the groups. The findings revealed statistically significant differences ($p < 0.05$) in favor of the experimental group in specific systems thinking skills, including analysis, synthesis, recognizing relationships, and overall perception. These results suggest that STEM-based activities effectively enhance students' cognitive abilities, allowing them to engage in complex scientific reasoning. The study underscores the importance of STEM-based learning in elementary science education and recommends integrating STEM activities to promote higher-order thinking skills. Further research is encouraged to explore the long-term impact of STEM interventions, particularly among older students, to assess their broader influence on cognitive and academic growth.

Keywords:

STEM-based Learning, Systems Thinking Skills, Elementary Science Education, Cognitive Development, Experimental Study

Introduction

The 21st century has ushered in rapid and transformative changes across all aspects of life. Among the most dynamic of these is education, which has evolved to meet the demands of the 'Knowledge Economy Age' (Shahat & Al-Balushi, 2023). As educational outcomes play a pivotal role in societal advancement, there is a growing need to adopt teaching strategies that effectively prepare learners (Ohle-Peters & Shahat, 2025). Educators continue to seek instructional methods that align with modern pedagogical standards and promote active student engagement (Karalar et al., 2021). In science education, which emphasizes inquiry and hands-on learning, innovative strategies are essential for cultivating skills such as critical thinking, problem-solving, and analytical reasoning (Ambusaidi et al., 2022; Shahat et al., 2022). However, traditional instruction often prioritizes theoretical knowledge over practical application, limiting students' readiness for real-world problem-solving (Al-Qudayb, 2011).

To address this gap, interdisciplinary approaches like STEM (Science, Technology, Engineering, and Mathematics) have gained prominence. STEM promotes integrative, hands-on learning experiences that help students connect academic content to real-life contexts and develop key skills such as scientific reasoning, logical analysis, and decision-making (Al-Mazrouei & Olayan, 2020; Sanders, 2009; Shahat et al., 2024a). STEM-based activities are designed to merge content from multiple disciplines, enabling students to make meaningful connections and engage in deeper learning (Shahat et al., 2022, 2025). Such integration supports not only content mastery but also the development of cognitive skills that can be applied across subject areas. For example, 'systems thinking' has emerged as a valuable cognitive approach in STEM contexts. Unlike linear thinking, which follows sequential cause-and-effect reasoning, systems thinking encourages a holistic understanding of complex issues. It enables students to identify relationships, recognize patterns, and integrate analytical and synthetic reasoning to develop comprehensive models and solutions (Mohamed, 2009; Shahat et al., 2024c). It is a cognitive process that allows learners to represent and address problems based on their understanding of interconnected elements (Acar et al., 2018; York et al., 2019; Shahat et al., 2023). This study adopts the definition of systems thinking as a multifaceted cognitive skill that combines analysis, synthesis, and model-based reasoning (Al-Balushi et al., 2022).

Recognizing the growing emphasis on STEM education, this study explores its potential to enhance systems thinking skills among fourth-grade students. It contributes to the field by addressing a critical gap in the literature on how STEM-based activities influence cognitive development, particularly in younger learners (Shahat & Al-Amri, 2023). It also aligns with the goals of the Fourth Industrial Revolution, emphasizing the need to equip learners with skills necessary for navigating an increasingly interconnected world (Al-Balushi et al., 2022). Furthermore, this research supports the incorporation of STEM-based strategies into science curricula in the Sultanate of Oman, reinforcing their role in enhancing student engagement and real-world application of scientific concepts (Shahat et al., 2024c).

Problem Statement

Al-Ghamdi (2019) highlighted the need for educational approaches that enhance students' creative and innovative thinking skills. It is argued that educators need to encourage diverse forms of thought, such as critical thinking, that can benefit them in everyday contexts. These methods allow students to process and analyze the information they receive, helping them discover underlying relationships. Studies on systems thinking have demonstrated its positive impact on student achievement; some research has focused on what it is and how it is developed, while others have explored strategies for instilling these skills in students (Al-Jubaili, 2017; Al-Qudayb, 2011; Shahat et al., 2024a, 2025; York et al., 2019).

In order to meet Oman's Vision 2040 goals, the Ministry of Education is committed to enhancing and modernizing educational methods to obtain maximal outcomes. The vision 2040 goals expressly state that education must equip individuals to enter the workforce ready to compete and contribute to a knowledge-based economy. Educational program and curriculum development combined with diverse and innovative teaching methods are required to realize this vision (Oman Vision Document, 2019–2040; Shahat & Al-Balushi, 2023). Therefore, this study will investigate the use of STEM activities in science instruction to determine the impact of this contemporary approach on students' systems thinking.

A pilot survey was conducted by the researchers on a sample of Omani science teachers teaching grades 1-4. Findings revealed insights regarding students' proficiency in advanced thinking skills, including systems thinking. Almost 80% of the teachers surveyed believed students have limited ability to analyze and link relationships within scientific problems, although they perform well on straightforward questions. Additionally, 89% of the surveyed teachers indicated that students find it challenging to answer questions requiring higher-order thinking skills, such as analysis, synthesis, and a deep understanding of relationships. These findings align with previous studies, which have indicated the necessity of incorporating STEM-based activities to foster systems thinking and enhance students' cognitive and problem-solving abilities (Shahat et al., 2024d). Given Omani students' lack of thinking skills, the researcher's educational experience and familiarity with the field, and the absence—based on the researcher's knowledge—of any previous studies in Oman examining the impact of STEM activities on systems thinking among fourth-grade students, this study was initiated.

Aim and Research Question

The study aims to investigate the impact of STEM-based educational activities on developing systems thinking skills among fourth-grade science students. The research problem is summarized in the following main question: What is the impact of employing STEM-based activities in developing systems thinking skills among fourth-grade students?

To address this question, the study explores these specific sub-hypotheses:

H1.1: At the (α = 0.05) level, statistically significant differences in post-test scores for systems thinking skills will favor the experimental group over the control group.

H1.2: At the (α = 0.05) level, statistically significant differences between pre-test and post-test scores for the experimental group will favor the post-test, reflecting the impact of STEM-based activities.

Theoretical Framework and Literature Review

This section discusses the study's theoretical framework and reviews previous studies related to the current research topic, structured into two main areas: STEM education and systems thinking.

The STEM Approach

STEM is an interdisciplinary educational approach that integrates science, technology, engineering, and mathematics to foster engagement, motivation, and real-world relevance in learning (Al-Enezi & Al-Jabr, 2017; Shahat et al., 2023). The acronym STEM, which replaced the original "SMET" in 2001, reflects a deliberate shift to emphasize integration and the foundational role of these disciplines in driving innovation (Sanders, 2009). This rebranding aligned with global efforts to prepare students for the demands of the modern workforce. The British Association's report The Scientific Century, exemplified this shift in thinking by linking scientific advancement to national prosperity and calling for a renewed emphasis on science and mathematics education (Finegold et al., 2011).

The benefits of STEM education are well-documented. It encourages students to engage in real-world challenges, enhancing their critical thinking and problem-solving capabilities through engineering design principles and interdisciplinary integration (Jolly, 2016; Shahat et al., 2024a). It also promotes higher-order thinking, active engagement, collaboration, and communication—skills necessary for success in a technology-driven world (Shahat & Al-Amri, 2023). Each STEM discipline contributes distinct strengths: science develops inquiry and experimentation skills; technology applies scientific knowledge to practical contexts; engineering fosters design and spatial reasoning; and mathematics builds logical reasoning and pattern recognition (Shahat et al., 2024b). Together, these elements help students form deeper conceptual understanding and apply their learning across domains.

Applying STEM in practice requires a move away from traditional passive learning. The activities implemented typically involve hands-on, real-world problem-solving tasks. Pottenger et al. (2000) emphasized that STEM learning should be exploratory, collaborative, and rooted in real-life applications to make abstract concepts more meaningful for students (Shahat et al., 2024c). For example, students may be asked to design and build a model bridge using craft materials while applying principles of force, balance, and measurement (Al-Ghamdi, 2019). Another task could involve constructing a basic irrigation system for a school garden using recycled bottles, where students integrate knowledge of plant biology, fluid mechanics, and environmental sustainability (Abuthnain, 2021). These types of integrated activities require students to collaborate, hypothesize, test, and refine their designs—mirroring the engineering design process and reinforcing connections between science concepts and practical applications (Shahat et al., 2024a).

A growing body of research supports the effectiveness of STEM-based instruction. Al-Enezi (2020) found that integrating STEM activities improved academic achievement and scientific problem-solving among intermediate students. Similarly, Abdo (2019) reported enhanced creative thinking and academic performance among blind primary school students through STEM interventions. Karalar et al. (2024) confirmed that STEM-based strategies significantly improved higher-order thinking skills in comparison to traditional methods (Shahat et al., 2024a–c). These studies affirm that STEM approaches benefit diverse learners by strengthening both cognitive and practical competencies.

Beyond academic performance, several studies establish a strong relationship between STEM education and systems thinking. Abdurrahman (2023) found a significant positive correlation between STEM education and systems thinking and academic proficiency among basic education students. York et al. (2019) similarly identified links between STEM education and systems thinking and analytical decision-making. In Oman, Al-Lawatiya, (2014) reported significant differences in systems thinking based on gender and academic qualifications among Ministry of Education employees (Shahat et al., 2024a; Shahat & Al-Balushi, 2023). These findings support the integration of STEM-based learning as a tool to foster complex cognitive skills, including systems thinking.

STEM has become central to educational reform efforts globally (Acar et al., 2018). In Oman, it is a strategic component of educational modernization aligned with Vision 2040. Integrating STEM into science curricula is viewed as a means to enhance students' analytical, creative, and collaborative abilities, ensuring they are equipped for the demands of a rapidly evolving technological landscape (Shahat & Al-Balushi, 2023; Shahat et al., 2024d).

Systems Thinking

Systems thinking is a cognitive approach rooted in mathematics, engineering, and computer science (Klir & Ashby, 1991). It emphasizes the analysis of interrelated system components, encouraging learners to understand problems holistically rather than in isolation (Shahat et al., 2024c). This mode of thinking aligns with the complexities of real-world situations, where components continuously influence one another.

As a cognitive framework, systems thinking enables individuals to identify causal relationships, construct mental models, and interpret complex structures (Shahat et al., 2024b). Scholars have outlined various skills central to systems thinking, such as pattern recognition, system decomposition, cause-effect analysis, synthesis, and evaluation. Al-Kubaisi (2010) contributed a framework detailing these competencies. Al-Qudayb (2011) further organized them into four categories: understanding systemic relationships, system analysis, system synthesis, and system evaluation. These categories mirror the structured cognitive progression required for effective problem-solving. In practice, this sequence begins with recognizing systemic relationships—identifying how parts influence one another within a system. This is followed by system analysis, which involves breaking down complex systems into manageable components. System synthesis then requires integrating these components into coherent models, helping learners develop generalizations and practical applications. Finally, system evaluation involves assessing the integrity and functionality of the models, refining them based on feedback and outcomes (Shahat et al., 2023).

These processes enhance interdisciplinary learning and real-world problem-solving capabilities. The comparison of various frameworks in Table 1 shows a consistent emphasis across the literature on four core cognitive functions underpinning systems thinking: understanding systemic relationships, system analysis, synthesis, and evaluation.

By adopting Al-Qudayb's framework, the current study ensures a comprehensive approach to systems thinking skill development. This alignment strengthens the study's theoretical foundation and supports its focus on structured cognitive processes such as analysis, synthesis, and evaluation.

Al-Qudayb's (2011) framework was chosen because it offers a structured, cognitively grounded model that integrates these functions into a coherent developmental progression. Unlike other frameworks that may emphasize isolated skills or context-specific applications, Al-Qudayb's model supports a balanced and transferable approach to systems thinking. It emphasizes not only the decomposition and analysis of systems but also the reintegration and evaluation of ideas—key capabilities for tackling real-world complexity.

This choice directly supports the study's focus by aligning the research with a pedagogically sound and theoretically robust framework that reflects the mental processes targeted in systems thinking education. It enables the study to systematically explore learners' development across analytical, synthetic, and evaluative dimensions, ensuring that the intervention addresses both cognitive depth and interdisciplinary applicability.

Finally, previous empirical research—ranging from quasi-experimental to mixed-method designs—has informed the current study's methodology. These studies guided the formulation of activity types, implementation strategies, and tailored research instruments. They also contributed to the study's hypothesis development and data analysis framework, ensuring methodological coherence and academic rigor.

Table 1

Comparison of Systems Thinking Skills Across Frameworks

Skill Category	Al-Qudayb (2011)	Al-Kubaisi (2010)	Al-Hakim (2018)	Shahat et al. (2023)
Understanding Systemic Relationships	Recognizing relationships within a system	Pattern recognition	Identifying causal links and dependencies	Recognizing relationships
System Analysis	Identifying and breaking down system components	Decomposing and analyzing subsystems	Cause-effect analysis	Analysis
System Synthesis	Integrating concepts to construct models and derive generalizations	Constructing systems and generalizing patterns	Synthesizing knowledge into structured frameworks	Synthesis
System Evaluation	Verifying accuracy, assessing performance, and proposing improvements	Assessing system integrity	Evaluating and refining systemic models	Holistic perception

Methodology

Design

This study employed a quasi-experimental design. Quantitative data was collected through a systems thinking achievement test administered to 66 fourth-grade students at Ajyal Muscat Basic Education School in Al-Amarat, Muscat Governorate. The research was conducted during the second semester of the 2023/2024 academic year, spanning from March 25 to April 21. The participants, all enrolled in morning sessions, were divided into two groups: an experimental group that engaged in STEM-based activities and a control group that followed traditional teaching methods. This design was selected for its effectiveness in comparing the impact of STEM-based instruction versus traditional methods on the development of systems thinking skills (Creswell, 2019). The study focuses on assessing the effect of STEM-based activities on four specific systems thinking skills: analysis, synthesis, understanding relationships, and holistic perception.

The study was limited to Ajyal Muscat Basic Education School in Al-Amarat. It was selected due to its proximity to the researchers and the cooperation of both the science teacher and the school administration. The sample consisted of 66 fourth-grade students, evenly divided into 33 students in the experimental group and 33 in the control group. To ensure fairness and minimize bias, their teacher randomly assigned students to the experimental and control groups before the study's implementation. This random assignment aimed to eliminate potential confounding variables, ensuring a more accurate assessment of the impact of STEM-based activities on systems thinking development (Shahat et al., 2023).

Instruments

Teacher's guide for implementing STEM-based activities

To support the implementation of STEM-based activities for the experimental group, the researcher developed a comprehensive teacher guide designed to facilitate systems thinking within an interdisciplinary STEM framework. This guide includes an introduction outlining the significance of STEM integration, clearly defined learning objectives, a theoretical framework linking STEM disciplines with systems thinking, and a procedural framework providing detailed lesson plans for one unit and instructional strategies. The selected unit, "Electricity and Magnetism," from the fourth-grade science curriculum (second semester), was chosen due to its strong potential for fostering systems thinking through hands-on STEM activities (Shahat et al., 2023). The unit's content naturally lends itself to interdisciplinary exploration, allowing students to engage in experiments, engineering challenges, and mathematical modeling that deepen their understanding of complex scientific phenomena.

The researchers followed a structured, multi-phase process to ensure the guide's effectiveness, relevance, and alignment with STEM education principles. First, a comprehensive literature review was conducted, drawing on prior research on STEM-integrated education. Studies such as Karalar et al. (2024) and Al-Enezi (2020) provided insights into best practices for designing STEM-based activities that helped in creating the guide. This led to an emphasis on active learning, hands-on experimentation, and interdisciplinary problem-solving (Shahat & Al-Balushi, 2023).

Following the literature review, the unit "Electricity and Magnetism" was analyzed through the lens of STEM education to ensure the effective integration of science, technology, engineering, and mathematics. Each lesson was created to allow a) scientific inquiry through experimentation and observation, b) interaction with technological applications such as simulations and digital tools, c) active participation in engineering challenges where students design simple circuits, electromagnets, and energy transfer models, and d) the application of mathematical reasoning through calculations, measurements, and data interpretation. This approach ensured that students engaged in interdisciplinary problem-solving while developing critical thinking skills.

The first draft of the teacher guide included an introduction explaining the role of STEM in developing systems thinking, a theoretical framework, and connections to real-world applications reinforcing the relevance of STEM-based learning. The guide aligned with the Omani Ministry of Education curriculum and the Cambridge international curriculum to ensure coherence with national and international educational standards. It incorporated structured lesson plans that included learning objectives, instructional activities, assessment strategies, and time allocations for various activities to ensure a balanced mix of hands-on, collaborative, and inquiry-based learning. Additionally, group-based and interdisciplinary STEM activities were designed to foster teamwork, creativity, and problem-solving.

To validate the guide's practicality, clarity, and instructional effectiveness, it was reviewed by six science education experts, including STEM-specialized teachers, Ministry of Education supervisors, and university educators with expertise in science education. Their feedback was used to refine the guide and improve its usability, lesson clarity, activity feasibility, and instructional scaffolding. The final version ensures that teachers can effectively implement STEM-based learning and facilitate student engagement with scientific inquiry, engineering design, and real-world problem-solving (Shahat et al., 2024a).

Systems thinking test

The systems thinking test was designed to evaluate students' proficiency in key cognitive skills associated with systems thinking. Drawing from Al-Qudayb (2011) and recent studies (Shahat et al., 2024b), the researcher identified four primary systems thinking skills:

1. Analysis: breaking down complex systems into simpler subsystems, enabling students to recognize interconnections and understand systemic structures.
2. Synthesis: combining and integrating subsystems to construct a cohesive, functional system that promotes holistic problem-solving.
3. Recognizing Relationships: understanding connections between system components and their interactions within larger frameworks.
4. Holistic Perspective: developing a comprehensive understanding of topics while maintaining attention to details in order to foster a systems-level view of knowledge.

These skills guided the development of activities and test questions, ensuring a direct assessment of STEM activities' impact on systems thinking among fourth-grade students (Shahat et al. 2024c).

The test consisted of 16 multiple-choice questions, evenly distributed across the four identified skills:

- Analysis: 4 questions
- Synthesis: 4 questions
- Recognizing Relationships: 4 questions
- Holistic Perspective: 4 questions

The test was designed to match the age level of the target students and was short enough to be completed within one 45-minute lesson. It consisted of a balanced allocation of questions to provide a comprehensive measure of students' systems thinking capabilities across all targeted skills (Shahat et al., 2024d).

Validity and reliability

The systems thinking test was initially developed to align with cognitive abilities appropriate for fourth-grade students. The first draft consisted of 20 questions, designed to comprehensively evaluate students' proficiency in analysis, synthesis, recognizing relationships, and holistic perspective. To ensure the content validity of the test, a panel of experts reviewed the instrument. This panel included four science teachers, two specialists with master's degrees in science curricula and teaching methods, and an educational supervisor.

Following their feedback, adjustments were made to improve the test's clarity, suitability, and appropriateness for fourth-grade students. Specifically:

- Certain questions were removed, and others rewarded to ensure comprehensibility and age appropriateness.
- The number of questions was reduced, making the test more manageable and accessible for young learners.
- The final version was refined to better align with the educational level and STEM-based instruction implemented in the study (Shahat et al., 2024a).

To establish the reliability of the test, it was administered to a pilot sample of 35 fourth-grade students, and Cronbach's alpha was calculated using SPSS. The reliability analysis produced an overall coefficient of 0.76, indicating a satisfactory level of internal consistency, as recommended by Gay & Mills (2022). In psychometric testing, a coefficient closer to 1 reflects stronger reliability. This value confirms that the test reliably measures systems thinking skills among fourth-grade students (Shahat et al., 2024b).

The Cronbach's alpha coefficients for each system's thinking skill were also analyzed to ensure consistency across individual components of the test (see Table 2).

Although the Holistic Perspective skill scored slightly lower (0.65) than other dimensions, this result is not unusual and can be attributed to the broader, more abstract nature of holistic thinking. As holistic perspective focuses on big-picture reasoning, interconnected relationships, and overarching system dynamics, it is inherently more complex and subjective to assess compared to more structured cognitive skills like analysis or synthesis. Despite this, the score remains

Table 2
Cronbach's alpha coefficients for each system's thinking skill

Systems Thinking Skill	Cronbach's Alpha Coefficient	Reliability Interpretation
Analysis	0.79	High Internal Consistency
Synthesis	0.74	Satisfactory Reliability
Recognizing Relationships	0.77	Satisfactory Reliability
Holistic Perspective	0.65	Acceptable Reliability
Overall	0.76	Satisfactory reliability

within an acceptable range for the study's purposes and aligns with commonly accepted standards for reliability in educational research (Field, 2009). Furthermore, similar findings have been observed in previous research where higher variability in holistic thinking measures was noted due to its reliance on integrative, less linear cognitive processes, reinforcing the validity of this result.

With validity and reliability confirmed, the test was finalized for implementation in the main study. The results validate the test as a consistent and reliable instrument for measuring systems thinking skills among fourth-grade students. These reliability coefficients underscore the instrument's potential to accurately and consistently evaluate the targeted skills across the experimental and control groups (Field, 2009).

Procedures and data analysis

Two fourth-grade classes were randomly assigned to form experimental and control groups. To ensure equivalence between the groups before the intervention, an independent samples t-test was conducted on pre-test scores, calculating both mean scores and standard deviations for each systems thinking skill (Creswell, 2019; Shahat et al., 2024a).

The t-test results confirmed no statistically significant differences between the control and experimental groups across all systems thinking skills, thus establishing group homogeneity prior to the intervention. The results were as follows in Table 3:

These results confirm the absence of statistically significant differences between the groups, verifying group homogeneity and ensuring a reliable basis for post-intervention comparisons (Shahat et al., 2024b).

During the instructional phase, students in the experimental group participated in STEM-based activities specifically designed to enhance systems thinking skills, while the control group received traditional instruction. Upon completion of the instructional period, a systems thinking test was administered as a post-test to both groups to assess the impact of STEM-based learning (Shahat & Al-Balushi, 2023).

To evaluate the effectiveness of the intervention, several key statistical analyses were conducted:

1. Descriptive statistics (means and standard deviations) were calculated to establish baseline scores and track changes in post-test performance (Field, 2009).

2. Independent samples t-test was conducted to confirm initial group equivalence and identify any statistically significant differences in post-test scores between the experimental and control groups.

3. Paired samples t-test was used to compare pre-test and post-test differences within each group, providing insights into the specific impact of STEM-based activities on systems thinking skills in the experimental group compared to the control.

These statistical procedures comprehensively assessed the impact of STEM-based instruction, confirming the method's reliability and its effectiveness in enhancing cognitive skills related to systems thinking (Shahat et al., 2024b).

Results

To address the research question, What is the impact of employing STEM-based activities on the development of systems thinking skills among fourth-grade students?, and to test Hypothesis H1.1—At the α = 0.05 level, statistically significant differences in post-test scores for systems thinking skills will favor the experimental group over the control group—an independent samples t-test was conducted. The post-test scores for systems thinking skills were analysed to examine differences between the experimental and control groups, as summarized in Table 4.

Table 3

t-test results for the control and experimental groups across all systems thinking skills prior to the intervention

Systems Thinking Skill	Control Group Mean (SD)	Experimental Group Mean (SD)	t-value	p-value
Analysis	0.43 (0.24)	0.39 (0.26)	0.73	0.350
Synthesis	0.40 (0.29)	0.36 (0.24)	0.69	0.284
Recognizing Relationships	0.25 (0.24)	0.26 (0.22)	-0.23	0.478
Holistic Perspective	0.36 (0.24)	0.31 (0.27)	0.83	0.434
Overall Score	0.36 (0.12)	0.33 (0.14)	1.02	0.607

Table 4

Independent Samples t-Test Results for Systems Thinking Skills Post-Test Scores

Systems Thinking Skills	Control Group (n = 33)		Experimental Group (n = 33)		t-value	p-value	Direction of Differences
	Mean	SD	Mean	SD			
Analysis	0.45	0.26	0.79	0.19	-6.16	< .001	Experimental
Synthesis	0.45	0.27	0.79	0.24	-5.46	< .001	Experimental
Understanding Relationships	0.44	0.28	0.79	0.18	-6.13	< .001	Experimental
Holistic Perception	0.48	0.27	0.74	0.25	-4.19	< .001	Experimental
Overall test	0.45	0.12	0.78	0.11	-11.67	< .001	Experimental

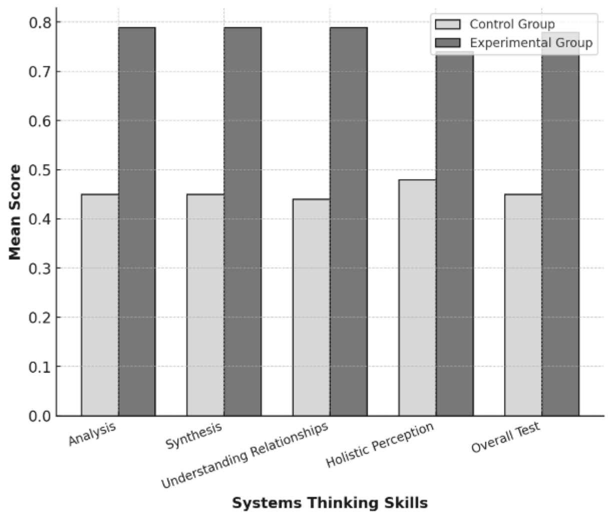
Note. t = t-value; p = p-value. Significance level: p < .05.

June 2025, Volume 17, Issue 4, 629-641

As shown in Table 4, the results revealed statistically significant differences in the post-test mean scores for systems thinking skills between the experimental and control groups, particularly in the skill of Understanding Relationships ($t(32) = -6.13$, $p < .05$). The overall t-value for systems thinking skills was -11.67, indicating a considerable difference favoring the experimental group. The mean scores for the control group ranged from 0.44 to 0.48, while the experimental group's mean scores ranged from 0.74 to 0.79. These findings suggest that STEM-based activities had a positive impact on students' systems thinking skills. Figure 1 illustrates the results.

Figure 1:

Mean Systems Thinking Skills Post-Test Scores for Experimental and Control Groups (N=66)



A paired samples t-test was conducted to compare pre-test and post-test scores for the experimental group across five domains and to test Hypothesis H1.2: At the α = 0.05 level, there will be statistically significant differences between pre-test and post-test scores for the experimental group, favoring the post-test, thereby reflecting the impact of STEM-based activities. The results are presented in Table 5.

Table 5

Paired Samples T-Test Results for Pre- and Post-Tests

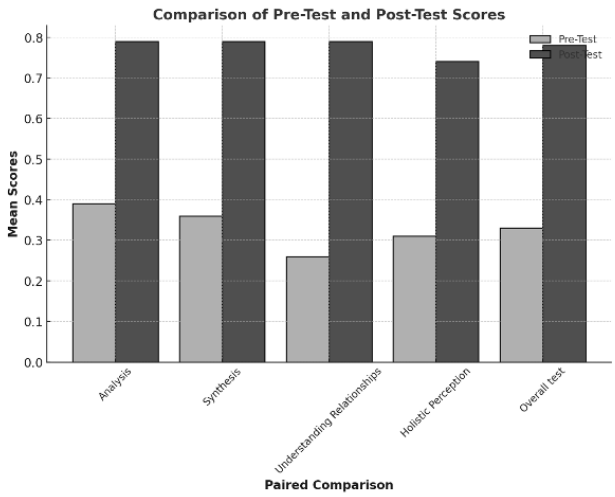
Paired Comparison	M (Difference)	SD	SE	95% CI (Lower)	95% CI (Upper)	t	df	p	Direction of Difference
Analysis	0.40	0.32	0.06	0.29	0.51	7.14	32	< .001	Post
Synthesis	0.43	0.34	0.06	0.31	0.55	7.28	32	< .001	Post
Understanding Relationships	0.53	0.28	0.05	0.43	0.63	10.71	32	< .001	Post
Holistic Perception	0.43	0.37	0.06	0.30	0.56	6.71	32	< .001	Post
Overall test	0.45	0.18	0.03	0.39	0.51	14.52	32	< .001	Post

Note. M = Mean Difference; SD = Standard Deviation; SE = Standard Error; CI = Confidence Interval; t = t-value; df = degrees of freedom; p = p-value. Significance level: p < .05.

The results indicated statistically significant improvements across all domains in the post-test compared to the pre-test. The largest mean difference was observed in "Understanding Relationships" ($M = 0.53$, $SD = 0.28$, $t(32) = 10.71$, $p < .001$), followed by "Overall test" ($M = 0.45$, $SD = 0.18$, $t(32) = 14.52$, $p < .001$). These findings suggest that the intervention had a positive impact on students' performance across all evaluated dimensions. Figure 2 illustrates the results.

Figure 2:

Mean Systems Thinking Skills Pre-Post-Test Scores for the Experimental Group



Discussion

This section analyses the study's findings in relation to existing research, highlighting key improvements in systems thinking skills and potential influencing factors. The results of this study indicate that STEM-based activities positively influenced the systems thinking skills of fourth-grade students, with statistically significant improvements across all assessed domains. Notably, the "Understanding Relationships" skill showed the greatest enhancement in the experimental group, highlighting its strong development through the intervention. This particular finding may be attributed to the nature of STEM-based activities, which inherently emphasize identifying patterns, connections, and interdependencies—core elements of understanding relationships within systems. Such activities often require students to observe how components interact, make predictions based on observed trends, and modify their solutions accordingly promoting a recursive process that nurtures relational and systems-oriented thinking. This outcome aligns with findings by researchers such as Abu Musa (2021), who suggests that because these approaches emphasize recognizing structural relationships within systems and developing mental models to address challenges, STEM approaches enhance complex cognitive skills, including those grounded in design thinking and systems analysis. Understanding relationships is a fundamental aspect of both problem-solving and model-building. In STEM tasks, learners move beyond rote procedures and are instead invited to think strategically—envisioning dynamic systems, identifying feedback loops, and recognizing how modifying one variable can impact others. STEM-facilitated design thinking, which involves model-building, empathy, and iterative solution testing, fosters a level of advanced cognitive engagement that appears beneficial for developing skills related to recognizing and analyzing relationships within systems (Shahat et al., 2023).

Similarly, Darwish's (2024) study on spatial abilities and geometric thinking in STEM students supports the idea that STEM instruction is effective in fostering relational thinking skills, which are closely tied to understanding systems. While analytical thinking is also a key cognitive skill developed through STEM education, the primary focus here is on how STEM-based activities enhance students' ability to recognize connections, patterns, and interdependencies, reinforcing the improvements observed in the "Understanding Relationships" skill (see Figure 3).

Figure 3:
Example of students' work in the experimental group.

Moreover, the study's findings extend existing research by demonstrating that even at the elementary level, students can benefit cognitively from STEM experiences if activities are well-structured, appropriately scaffolded, and contextually meaningful. This has implications for the early introduction of systems thinking concepts, which are often reserved for older students. By embedding systems-based reasoning in younger learners' educational experiences, educators can cultivate foundational cognitive habits that support lifelong scientific literacy.

However, despite the overall statistically significant improvements across all domains in the post-test compared to the pre-test, several contextual factors may have limited the extent of skill development. The study was conducted during the second semester, coinciding with Ramadan, which resulted in a shortened instructional period and disruptions due to Eid holidays. Additionally, the school operated on a two-shift system, where lesson durations were reduced by 10 minutes (e.g., 45 minutes to 35 minutes), potentially limiting the depth and continuity required for students to engage with and internalize the STEM-based learning activities fully. This limited exposure may not have provided sufficient time for students to grasp the interconnected nature of STEM learning, particularly in ways that support the comprehensive development of systems thinking skills (Shahat & Al-Balushi, 2023).

The data supported the second hypothesis, which predicted significant differences between pre- and post-test scores favouring the experimental group. This finding aligns with prior research; for example Pertiwi et al. (2024) observed significant gains in critical thinking following a STEM intervention. Al-Enezi's (2020) study also noted similar findings, where STEM-based activities significantly improved problem-solving and academic achievement among intermediate students. These previous studies highlight the potential for STEM activities to provide a rich, integrative learning environment that fosters a variety of cognitive skills, especially when sufficient time and curricular flexibility are provided.

Beyond individual cognitive gains, these findings reinforce the broader educational value of STEM in supporting national and global goals related to 21st-century skills and the Fourth Industrial Revolution. Developing systems thinking skills through STEM education not only benefits academic performance but also prepares students for future challenges involving complex problem-solving, sustainability, and innovation (Al-Balushi et al., 2022; Abdurrahman et al., 2023). As such, STEM should not be viewed merely as a pedagogical trend, but as a strategic foundation for cultivating adaptive, systems-literate citizens.

The findings suggest that while STEM activities show promise in fostering systems thinking, factors such as instructional duration and curriculum structure may significantly influence their effectiveness. Future studies could be considered:

1. Extended interventions over multiple semesters allow for progressive development of systems thinking skills.
2. Adjustments to lesson duration, particularly in educational settings where STEM education is introduced in split-shift schedules or during condensed academic periods.
3. A more integrated STEM curriculum, ensuring that students have ample time to engage with hands-on learning experiences and develop higher-order cognitive skills (Shahat et al., 2024c).

June 2025, Volume 17, Issue 4, 629-641

Additionally, qualitative follow-up studies could explore how students conceptualize system interactions during STEM tasks, providing richer insights into cognitive processes that standardized tests may overlook. Investigating teacher implementation practices and student engagement patterns could also help refine future program design.

Such modifications may yield a more comprehensive development of systems thinking skills, better reflecting the full potential of STEM-based learning and its impact on student cognition.

Limitations

One limitation of this study was the sample size and scope, as it was conducted in a single school with two fourth-grade classes. While the study provides valuable insights, the findings may not be fully generalizable to broader educational contexts. A larger sample, encompassing multiple schools with varied instructional settings, would offer a more comprehensive understanding of how STEM-based learning influences systems thinking skills in different learning environments.

A second limitation relates to the duration and structure of instructional time. The intervention was conducted during the second semester, which coincided with the holy month of Ramadan and the Eid holidays. As a result, the available teaching time was compressed. Moreover, the school's two-shift schedule reduced the standard lesson duration to just 10 minutes. These time constraints may have restricted students' opportunities for deep engagement with the STEM activities, particularly those requiring iterative exploration and extended model-building—both essential for developing systems thinking.

Another important consideration is the potential influence of the classroom teacher. Although efforts were made to standardize instruction across both the control and experimental groups, variations in teacher experience, enthusiasm, or familiarity with STEM practices may have influenced implementation fidelity and student responsiveness. Future studies should consider either using multiple teachers to dilute individual influence or employing video monitoring and fidelity checklists to ensure consistent delivery.

In addition, external environmental factors—such as classroom resources, parental support, and students' prior exposure to inquiry-based learning—may have acted as confounding variables, despite efforts to maintain equivalency between groups. These factors were not measured in this study but could have had an indirect effect on students' ability to benefit from the intervention.

Implications

Despite its limitations, this study highlights the potential of STEM-based activities in enhancing systems thinking skills among elementary students—particularly in recognizing relationships within systems. To support practical application in educational contexts, the following implications are offered:

- Integrate STEM into the elementary curriculum to promote early development of cognitive skills such as problem-solving, analysis, and relational thinking. These skills form the foundation for more complex learning in higher grades and across disciplines.

- Design STEM activities that emphasize identifying and analyzing relationships within complex structures. Such focus helps students develop transferable systems thinking abilities applicable to science, mathematics, and beyond.

- Ensure sufficient instructional time for STEM lessons. Where possible, adopt flexible or extended periods to allow deep engagement with STEM tasks. If longer periods are not feasible, strategically structure shorter lessons to retain core inquiry and reflection components.

- Consider scheduling and classroom conditions as critical factors in implementation. Reduced lesson times and two-shift systems can limit the depth of student interaction with STEM content, thus requiring thoughtful instructional design.

- Promote a holistic and interdisciplinary learning environment where students are encouraged to make connections across scientific and mathematical concepts. This helps cultivate systems thinking as a long-term competency from early education stages.

By addressing these instructional and structural factors, educators and curriculum designers can optimize the integration of STEM-based education to enhance students' systems thinking and equip them for future academic and real-world challenges.

Future Directions

Building on the findings of this study, future research should consider extending the duration of STEM interventions over multiple semesters to provide students with continuous exposure, allowing for the progressive and comprehensive development of systems thinking skills. A longer intervention period would enable students to reinforce and internalize STEM concepts more effectively, supporting deeper cognitive engagement and the gradual mastery of complex problem-solving processes (Shahat, Al-Balushi, & Al-Amri, 2023). Given that STEM education fosters engineering design thinking and cognitive flexibility, extended exposure may lead to more sustainable cognitive development in systems thinking-related skills (Shahat et al., 2024a).

Further studies should explore STEM integration in diverse educational models, including those with flexible or extended lesson times, to determine the optimal instructional conditions for fostering systems thinking skills. Investigating how different teaching structures, such as block scheduling or inquiry-based learning models, impact STEM learning outcomes would provide valuable insights for curriculum design (Shahat & Al-Balushi, 2023). Additionally, expanding the sample size and including schools with varied instructional settings—such as those operating on single-shift versus two-shift systems—could enhance the generalizability of the findings and help identify specific factors that contribute to successful STEM implementation across different learning environments (Shahat, Al-Balushi, & Al-Amri, 2024b).

Moreover, future research should broaden the scope to explore the impact of STEM activities on other essential cognitive skills, such as critical thinking, creativity, and problem-solving. Studies have shown that STEM-based learning enhances students' ability to think critically and innovate solutions to real-world challenges (Shahat et al., 2024c). Since STEM education emphasizes interdisciplinary thinking and practical applications, it is crucial to investigate how these approaches contribute to students' ability to synthesize information and apply knowledge across different disciplines (Shahat et al., 2024d).

Longitudinal studies could provide valuable insights into the long-term effects of early STEM exposure on students' academic trajectories, particularly in science, technology, engineering, and mathematics disciplines. Tracking students over several years would help determine how early engagement in STEM influences future academic performance, career interests, and STEM-related professional pathways (Shahat et al., 2024e). Additionally, examining gender differences in STEM learning outcomes could provide critical perspectives on how to provide equitable STEM education opportunities for all students (Al-Balushi et al., 2022).

Lastly, future research could investigate the role of teacher training in enhancing the effectiveness of STEM interventions. Understanding how educators' expertise, instructional strategies, and professional development programs influence STEM implementation could inform policies aimed at strengthening STEM education at both the classroom and institutional levels (Shahat et al., 2023). Studies emphasize the importance of teacher preparation programs in equipping educators with the skills necessary for effectively implementing STEM-based learning (Shahat et al., 2024a). By addressing these research areas, future studies can contribute to the continuous improvement of STEM education, ensuring that it effectively supports students' cognitive and professional growth in an increasingly technology-driven world.

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