

Cultivating Elementary Students' Systems Thinking with an STH Strategy: A Design-Based Study in the “Three States of Water” Unit

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Abstract:

In an era of rapid technological development and increasing uncertainty, systems thinking is essential for enabling learners to understand complex phenomena and address real-world problems. Despite its importance, elementary science classrooms often emphasize fragmented factual knowledge rather than integrated reasoning, limiting students' ability to construct coherent mental models. Guided by the Systems Thinking Hierarchical (STH) model, this study developed a multi-phase instructional strategy that embeds problem-solving processes within progressively deepening system understanding. Using a design-based research approach, three iterative cycles were conducted in Grade-5 science classrooms to refine the strategy and associated learning activities. The final STH-aligned framework comprises six components: creating inquiry contexts, identifying system elements, mapping relationships, representing dynamic change, articulating mechanistic explanations, incorporating hidden variables, and applying systemic principles to authentic problems. Systems-thinking performance was assessed through STH-aligned concept maps. Findings indicate that the STH-based strategy effectively enhances elementary students' ability to identify system components, reason about causal dynamics, and transfer systemic principles to new contexts. The study provides an empirically supported instructional approach and assessment pathway for fostering systems thinking in elementary science education.

Keywords:

Systems Thinking, Elementary Science Education, STH Model, Design-based Research, Concept Maps

1. Introduction

The accelerating complexity of contemporary scientific, technological, and environmental challenges has underscored the need for cultivating systems thinking from the earliest stages of education. As societal issues increasingly involve

multifactor interactions, nonlinear dynamics, and causal networks, citizens must be able to interpret phenomena not as isolated events but as parts of interdependent systems. Within this context, systems thinking—broadly defined as the ability to identify system components, uncover relationships, and reason about dynamic changes—has become an essential dimension of scientific literacy. Empirical research has shown that even young learners can begin to coordinate elements, processes, and causal relations when provided with appropriate learning supports [1,2]. Yet despite its recognized importance, systems thinking remains insufficiently developed in elementary science instruction, where fragmented knowledge acquisition and surface-level observation often predominate.

Curricular frameworks in many countries emphasize that scientific understanding requires integrating concepts across topics and recognizing patterns and mechanisms that underlie observable events. The Next Generation Science Standards [3] position “systems and system models” as a central crosscutting concept, encouraging instruction that highlights interactions, feedback loops, and model-based reasoning. Similarly, China’s Compulsory Education Science Curriculum Standards [4] call for strengthening conceptual connections and engaging students in real-world problem contexts where scientific knowledge must be applied systemically. These frameworks reflect a broader recognition that elementary science should move beyond discrete facts toward the development of transferable reasoning structures that support interpretation of complex real-world phenomena.

Despite such policy aspirations, existing classroom practices often fall short of fostering systemic reasoning. Elementary science lessons frequently introduce evaporation, condensation, or state change as discrete phenomena without engaging students in the underlying variables—such as temperature, humidity, or energy transfer—that interact to produce observable outcomes. This emphasis on isolated observations limits students’ capacity to identify hidden factors, trace causal sequences, or reason about dynamic interactions over time. As a result, students form fragmented mental models that hinder the development of scientific explanation and prediction. These challenges highlight the need for pedagogical approaches that make systemic relationships visible, accessible, and meaningful for young learners.

Theoretical frameworks of systems thinking provide important foundations for such instructional innovation. The Iceberg Model [5] conceptualizes systemic reasoning as a progression from identifying surface events toward recognizing patterns, structures, and underlying mental models. Riess and Mischo [6] further argue that systems thinking comprises interconnected conceptual, procedural, and reflective components, each of which must be deliberately supported. Empirical studies by Assaraf and Orion (2005) show that students’ systemic understanding evolves gradually, beginning with the identification of system elements and progressing toward the recognition of causal and dynamic relationships. Subsequent work by Assaraf and colleagues [7] demonstrates that students’ explanations become more mechanistic when they learn to coordinate multiple representations and link observable events with underlying processes. Together, these findings suggest that systems thinking is neither an innate ability nor a fixed trait but a developmental competence that can be fostered through structured instructional strategies.

The Systems Thinking Hierarchical (STH) model proposed by Tripto, Assaraf, and Amit [8] provides a particularly promising framework for operationalizing these ideas in classroom instruction. The STH model articulates three progressively complex

levels: identifying system components and processes, recognizing relationships and dynamic interactions, and applying systemic principles to novel contexts. Each level contains observable indicators that can guide both instructional design and assessment. Importantly, the STH model aligns with conceptualizations of systems thinking as a developmental trajectory rather than a binary skill, offering a usable structure for scaffolded learning. However, research investigating the implementation of the STH model in elementary science classrooms remains limited. Without explicit pedagogical routines, teachers often struggle to transform the STH indicators into age-appropriate activities, and assessments rarely capture relational or dynamic reasoning, instead favoring factual recall.

Design-Based Research (DBR) offers a methodology well-suited to addressing these challenges by bridging theoretical frameworks with practical classroom needs. DBR involves iterative cycles of design, enactment, analysis, and refinement, allowing researchers and teachers to co-construct interventions that are both theoretically grounded and contextually feasible [9,10]. DBR has proven effective in supporting model-based reasoning, inquiry processes, and conceptual understanding by generating design principles rooted in classroom realities [11,12]. In the context of systems thinking, DBR enables researchers to track how learners' representations and reasoning evolve across iterations, providing insight into the scaffolds that effectively promote hierarchical progression in systemic understanding.

Guided by both the STH framework and DBR methodology, the present study seeks to develop and refine an instructional strategy tailored to the Grade 5 science unit "Three States of Water." This unit constitutes a rich conceptual domain for systems thinking: evaporation, condensation, and phase changes are governed by multiple interacting variables, including temperature, humidity, energy transfer, and environmental conditions. These variables are often invisible, making the topic an ideal context for introducing students to the distinction between observable events and underlying mechanisms. Through three iterative DBR cycles conducted in authentic classroom settings, we developed a six-phase instructional strategy designed to foster progression across the three levels of the STH model. The strategy emphasizes identifying system components, mapping causal relationships, representing dynamic changes over time, uncovering hidden parameters, and applying systemic principles to interpret everyday phenomena. Concept maps aligned with STH indicators were integrated as both formative and summative assessments, enabling systematic tracking of students' learning trajectories. Based on the Systems Thinking Hierarchical (STH) model, the present study conceptualizes students' systemic reasoning across three levels (Table 1). These levels informed both the instructional design and the assessment framework.

Table 1. *Systems Thinking Hierarchical (STH) Model and Associated Competencies (Adapted from Tripto, Assaraf, & Amit, 2013 [8]).*

STH Level	Description	Associated Competencies
Level 1: Analysis of System Components	Identifying the elements that make up a system.	A1. Identify the components that constitute the system.
Level 2: Integration of System Components	Understanding relationships and dynamic interactions among components.	S1. Recognize relationships among system components. S2. Understand that systems are dynamic and change over time. S3. Represent relationships among components using conceptual or visual

		models. S4. Identify cyclic or feedback structures within the system.
Level 3: Implementation of Systemic Strategies	Applying systemic principles to interpret and solve real-world problems.	I1. Conceptualize a system and apply general systemic strategies to address problems. I2. Identify and reason with hidden variables or unobservable factors within the system. I3. Make predictions or propose solutions based on interactions among system components.

This study aims to investigate (a) the effectiveness of the STH-based instructional strategy in enhancing elementary students' systems thinking, (b) the evolution of students' representational and reasoning patterns across DBR cycles, and (c) the design principles that emerge from linking theoretical models with classroom enactment. By achieving these aims, the study contributes to bridging the longstanding gap between curricular expectations and classroom practices in systems thinking education. It offers a replicable, theoretically grounded, and contextually adaptable approach to supporting systemic reasoning in elementary science, providing valuable guidance for curriculum developers, teacher educators, and classroom practitioners seeking to promote deeper scientific understanding.

2. Method

2.1. Research Design

This study employed a Design-Based Research (DBR) methodology to develop, refine, and evaluate an instructional strategy aligned with the Systems Thinking Hierarchical (STH) model. DBR is characterized by iterative cycles of design, enactment, analysis, and redesign conducted in naturalistic educational settings [9]. It is particularly suited to research that aims to generate theory-informed instructional interventions while ensuring feasibility for real classroom conditions. Unlike fixed experimental designs, DBR enables the progressive refinement of pedagogical strategies based on continuous classroom evidence—an essential feature for research focused on improving complex reasoning processes such as systems thinking [11].

In this study, the four canonical DBR processes were operationalized into three practical phases—Preparation, Design and Implementation, and Analysis and Refinement—reflecting the integrated nature of school-based instructional design. These phases were enacted iteratively across three cycles within one semester. Figure 1 illustrates the DBR process used in the study and how each phase informed the next cycle of refinement.

Guided by this methodological orientation, the present study implemented three iterative DBR cycles across one semester. Each cycle consisted of (a) co-design sessions between the researcher and an experienced science teacher, (b) classroom enactment of the designed activities, (c) systematic data collection, and (d) evidence-based redesign. These steps correspond to the Preparation, Design and Implementation, and Analysis and Refinement phases shown in Figure 1. The overarching aim was to translate the STH model into a practical, age-appropriate instructional sequence capable of fostering progression in elementary students' systems thinking.

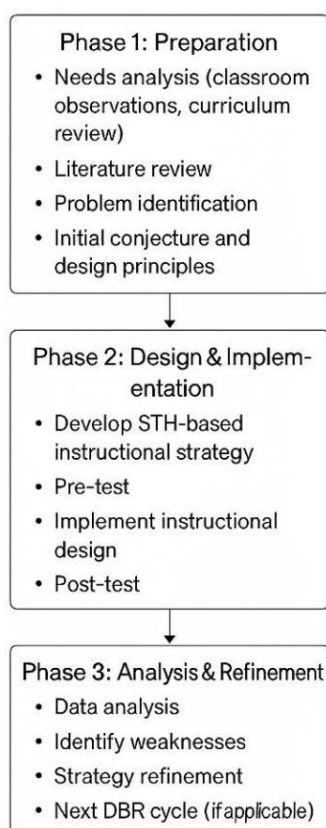


Figure 1. Design-Based Research Process Used in the Study.

2.2. Participants and Context

The study was conducted at M Elementary School, a medium-sized public school in Shanxi Province, China, which followed the Compulsory Education Science Curriculum Standards (MOE, 2022). Two intact Grade 5 classes participated: one served as the treatment group ($n = 38$), receiving the STH-aligned instructional strategy, and the other served as the comparison group ($n = 38$ for pre-test; $n = 37$ for post-test), receiving conventional instruction. Students were 10–11 years old. Random assignment was not feasible due to intact class structures, a common constraint in school-based DBR research.

Both classes were taught by the same science teacher, who had 15 years of teaching experience and was recognized as a district-level exemplary teacher, strengthening the ecological validity of the intervention. Prior to implementation, the teacher participated in collaborative workshops introducing the STH model, the six-phase instructional strategy, and the use of concept maps and scenario-based tasks as assessment tools, reflecting DBR's emphasis on researcher–teacher partnership.

Parental consent and school authorization were obtained. Students were informed that participation was voluntary, that their data would be anonymized, and that their performance would not influence academic grades.

2.3. Instructional Context

The instructional context was the Grade 5 science unit Three States of Water, which includes three subtopics: (1) evaporation, (2) condensation, and (3) temperature and phase change. These topics provide a fertile context for systems-thinking development because they involve multiple interacting variables—such as temperature, humidity,

and energy transfer—many of which are invisible to learners and align closely with the STH model. The unit spanned nine lessons (three per subtopic), with each lesson lasting 40 minutes.

Recognizing the inherently systemic nature of these processes, the intervention was designed to move beyond simple demonstration experiments and instead support students in identifying components, mapping relationships, representing dynamic interactions, incorporating non-observable variables, and applying systemic principles to real-world problems.

2.4. Intervention: Six-Phase STH Instructional Strategy

The intervention operationalized the STH model into a six-phase instructional sequence. These phases were enacted for each of the three subtopics and iteratively refined across the DBR cycles. The six phases were as follows:

(1) Creating inquiry contexts and identifying system elements

Students observed everyday or experimental phenomena (e.g., fogged glasses, puddle evaporation), brainstormed relevant factors, and recorded visible variables using structured observation prompts.

(2) Abstracting contextual systems and mapping relationships

Students constructed preliminary representations by mapping causal relations (e.g., higher temperature → faster evaporation) using concept-map templates. Teacher-guided questioning supported the identification of direct and indirect relationships.

(3) Integrating information and recognizing dynamic change

Learners collected and interpreted data (e.g., temperature – time curves during heating) and produced graphs and flow diagrams to represent temporal patterns and feedback processes.

(4) Articulating regularities and mechanisms

Students compared their observations to identify consistent patterns (e.g., constant temperature during phase change) and collaboratively developed mechanistic explanations involving energy transfer and molecular behavior.

(5) Incorporating hidden variables

Instruction introduced non-observable variables—such as humidity, condensation nuclei, and thermal equilibrium—through guided demonstrations and representational prompts. Students revised their system models to integrate these abstract components.

(6) Applying systemic principles to real-world problems

Students solved scenario-based challenges (e.g., explaining why glasses fog up or how to minimize mirror condensation), drawing on the systemic models developed throughout the sequence.

These phases were enacted repeatedly across the three DBR cycles. Observation data, student representations, and interim assessments informed ongoing refinements to scaffolds, visual tools, and question sequences, enabling progressively stronger alignment with the STH developmental trajectory.

2.5. Comparison Condition

The comparison group received teacher-directed science lessons commonly used in local classrooms. Instruction emphasized demonstration experiments and textbook explanations, supplemented by short written exercises. Topics such as evaporation, condensation, and state change were introduced primarily through teacher demonstration and direct description of results. Students were not required to model relationships, represent dynamic interactions, identify non-observable variables, or apply systemic reasoning. This ensured a clear contrast between conventional conceptual instruction and the systemic, model-oriented approach of the intervention.

2.6. Instruments and Data Sources

A mixed-methods approach was used to capture students' progression in systems thinking. Student work was scored using standardized rubrics to ensure consistency. Item-level scoring sheets used during teaching were excluded from analysis because they served instructional rather than research purposes. Four primary data sources were used:

2.7. Concept-Map Assessment (STH Levels 1 & 2)

To assess students' understanding of system components and relationships, students completed a paper-based concept-mapping task centered on key ideas such as temperature, evaporation, condensation, and phase change. Fourteen indicators aligned with STH sub-skills were scored using a 0–2 rubric (0 = absent/incorrect, 1 = partially correct, 2 = accurate and integrated), with a maximum score of 28. Two raters independently scored all maps following a calibration session, yielding high inter-rater reliability (Cohen's $\kappa = 0.82$).

2.8. Scenario-Based Assessment (STH Level 3)

To evaluate systemic application, students responded to three open-ended real-world problems (e.g., “Why do glasses fog up when entering a warm room from the cold?”). Responses were scored from 0 to 3 based on completeness, accuracy, and evidence of relational or mechanistic reasoning (maximum score = 9).

2.9. Classroom Observations

The researcher and a trained assistant conducted structured observations focusing on students' representational practices (e.g., concept-map revisions, graph use), use of systemic vocabulary, and collaborative reasoning. These observations provided insight into learning processes and guided iterative redesign across DBR cycles.

2.10. Student Interviews

After each DBR cycle, ten students were randomly selected to participate in semi-structured interviews probing their understanding of relationships, dynamic interactions, and hidden variables (e.g., “How are temperature and humidity connected?”). Interviews were audio-recorded with consent and transcribed for thematic analysis.

3. Data Analysis

3.1. Quantitative Analysis

Group equivalence at pre-test was examined using independent-samples t-tests. Post-test differences between the treatment and comparison groups were analyzed using t-tests only (ANCOVA was not used in the present study). Effect sizes were

interpreted using conventional benchmarks (Cohen's d : .20 = small, .50 = medium, .80 = large). Means and standard deviations were reported for all outcome measures.

3.2. Qualitative Analysis

Interview transcripts and observational notes were analyzed using thematic analysis following Braun and Clarke's [13] guidelines. The coding scheme combined deductive codes aligned with STH sub-skills (e.g., components, relations, dynamics, application) and inductive codes emerging from student discourse. Two researchers independently coded 20% of the dataset ($\kappa = 0.81$) before resolving discrepancies through discussion. Triangulation across concept maps, interviews, and observations strengthened the validity of the qualitative findings.

3.3. Ethical Considerations

The study followed institutional ethical guidelines. Informed consent was obtained from parents, students, and the school. All data were anonymized, and participants were informed that they could withdraw at any time. The teacher voluntarily participated in co-design and classroom implementation.

4. Results

4.1. Pre-test Equivalence

Before the intervention, the treatment and comparison groups exhibited comparable systems-thinking performance across all three STH levels. As shown in Table 2, independent-samples t -tests revealed no significant differences in students' identification of system elements (Level 1), relational and dynamic reasoning (Level 2), or systemic application in real-world contexts (Level 3) (all $p > .05$). This baseline equivalence ensures that any subsequent group differences can be attributed to the instructional strategy rather than pre-existing disparities. Establishing such statistical parity is essential, given that systems thinking is known to vary widely across learners and can be influenced by prior exposure to scientific modeling practices. Table 2 presents the pre-test means, standard deviations, and t -test results for the two groups across the three STH levels.

Table 2. Pre-test Comparison of Systems Thinking Levels Between Treatment and Comparison Groups.

STH Level	Group	n	Mean	SD	t	p
Level 1: Component Analysis	Treatment	38	5.18	1.270	-0.175	.818
	Comparison	38	5.24	1.344		
Level 2: Integration of System Components	Treatment	38	3.55	1.606	-0.763	.376
	Comparison	38	3.28	1.392		
Level 3: Systemic Application	Treatment	38	2.61	1.175	-0.196	.804
	Comparison	38	2.66	1.169		

Note. Independent-samples t -tests indicated no significant pre-intervention differences between treatment and comparison groups across all STH levels.

4.2. Post-test Differences Across STH Levels

Following the intervention, the treatment group outperformed the comparison group across all three STH levels. As shown in Table 3, treatment students demonstrated greater accuracy and completeness in identifying relevant system elements (e.g., temperature, humidity, surface temperature), indicating substantial gains in conceptual

grounding. More importantly, they exhibited markedly stronger relational and dynamic reasoning. Their representations included causal chains (“higher temperature → faster evaporation → increased humidity”), temporal markers, and bidirectional feedback indicators, whereas comparison students’ responses remained focused on single-step or linear descriptions.

Table 3. *Final-Cycle Post-test Results.*

STH Level	Group	n	Mean	SD	t	p
Level 1	Treatment	38	11.18	1.14	3.43	.028
	Comparison	37	10.41	0.80		
Level 2	Treatment	38	6.24	1.03	3.10	.048
	Comparison	37	5.57	0.84		
Level 3	Treatment	38	6.37	0.99	4.77	.020
	Comparison	37	5.41	0.73		

The largest group difference appeared at STH Level 3, where treatment students produced more sophisticated systemic explanations for real-world scenarios such as fogging glasses or variable drying rates. These explanations often involved multi-factor interactions, references to hidden variables (e.g., humidity, condensation nuclei), and mechanistic reasoning grounded in energy transfer. This pattern suggests that the instructional strategy supported students in reorganizing their thinking to interpret phenomena as interacting, dynamic systems rather than isolated events.

The raw post-test means further illustrate the magnitude of these differences. At Level 1, the treatment group achieved a mean of 11.18, compared with 10.41 in the comparison group, $t(73) = 3.43$, $p = .028$. A similar pattern was observed at Level 2, where treatment students scored 6.24, exceeding the comparison group’s 5.57, $t(73) = 3.10$, $p = .048$. The largest gap occurred at Level 3: the treatment group obtained a mean score of 6.37, compared with 5.41 for the comparison group, $t(73) = 4.77$, $p = .020$. These results demonstrate that the instructional strategy produced improvements that were both statistically significant and practically meaningful.

4.3. Progression Across DBR Cycles

The following patterns reflect qualitative progression across the three DBR cycles rather than statistical comparisons. Concept-map analysis revealed a clear developmental trajectory across cycles. In Cycle 1, students’ maps consisted primarily of isolated observations such as “the water disappears” or “the cup becomes cold,” indicating a narrow focus on visible elements and limited integration of underlying processes. This pattern reflects what may be described as restricted causal integration—students attended to surface events but showed little awareness of the mechanisms linking them.

In Cycle 2, after relational scaffolds were introduced, students began coordinating a broader range of variables in their explanations. Their maps incorporated additional factors (e.g., temperature, humidity, air flow) and included explicit connections among them. Representational fluency—consistent with the patterns described earlier—also increased, with some students beginning to construct simple graphs or flow diagrams to depict temporal change. These developments indicate the early formation of more interconnected causal structures.

By Cycle 3, following the introduction of hidden-variable scaffolds, students demonstrated more integrated systemic reasoning. Their maps included both observable and non-observable factors and articulated multi-step causal mechanisms

such as energy transfer, dynamic equilibrium, and feedback conditions. These maps exhibited higher causal density and greater structural coherence, indicating a more mature understanding of evaporation- and condensation-related phenomena and reflecting the cumulative impact of iterative scaffold refinement across DBR cycles.

4.4. Growth in Systemic Reasoning: Qualitative Patterns

Interview data and classroom observations provided insight into the cognitive mechanisms underlying students' qualitative progression. Early in the intervention, students' reasoning was largely descriptive and focused on isolated events (e.g., explaining that "the mirror becomes wet because it is cold"). Few students acknowledged the role of invisible variables or dynamic changes. During Cycle 2, however, students began noticing underlying patterns, such as the movement of water vapor and the effects of temperature differences. They increasingly referred to non-observable variables (e.g., noting that "there is water in the air that we cannot see"), suggesting a shift from event-based reasoning toward emerging relational understanding.

By Cycle 3, students articulated multi-step mechanisms connecting physical processes. Their explanations incorporated ideas about energy transfer (e.g., vapor losing energy to a cold surface), equilibrium (e.g., stable temperature during phase change), and multi-variable causal interactions (e.g., drying depending jointly on temperature, humidity, and airflow). This shift reflects the development of causal density and hidden-variable awareness, two characteristics of more advanced systems thinking. These patterns were consistently observed across both student interviews and classroom observations.

Observational notes further revealed changes in representational practices. Early diagrams tended to depict events sequentially without showing interactions, whereas later diagrams included bidirectional arrows, proportional indicators (e.g., "faster/slower"), and temporal curves. Students also demonstrated increasing representational fluency, flexibly shifting between concept maps, graphs, and explanatory sketches depending on task demands. Such flexibility in representation has been identified in prior research as a key mechanism supporting the development of dynamic systems understanding.

4.5. Integrated Evidence of Systemic Learning

Evidence from all three data sources—quantitative results, student representations, and qualitative interviews—converged to show that the six-phase STH strategy effectively supported students' progression along the STH developmental trajectory. Rather than simply accumulating additional scientific facts, students reorganized their knowledge structures, demonstrated broader causal integration, and developed the ability to interpret scientific phenomena through the lens of interaction, mechanism, and change.

The iterative nature of the DBR cycles played a critical role in producing these gains. Each redesign introduced targeted scaffolds that addressed specific difficulties identified in the previous cycle, resulting in increasingly coherent system models, richer causal networks, and more robust mechanistic explanations. This triangulation of data sources strengthens the validity of the findings and illustrates a consistent pattern of improvement aligned with the theoretical expectations of the STH model.

Together, these results provide compelling support for the STH-aligned instructional strategy as an effective approach to cultivating systems thinking in elementary science. The convergence of quantitative improvement, representational sophistication, and qualitatively richer explanations highlights both the impact of the strategy and the processes through which students' systems thinking develops.

5. Discussion

This study aimed to design and evaluate a systems-thinking instructional strategy grounded in the STH model and developed through iterative DBR cycles. The findings provide convergent evidence that the six-phase strategy effectively supported Grade 5 students' development of systemic reasoning. This section interprets these findings in relation to existing literature, explains the developmental mechanisms underlying students' progress, discusses implications for elementary science education, and outlines limitations and directions for future research.

Quantitative and qualitative results showed clear alignment with the hierarchical progression described by Tripto, Assaraf, and Amit [8]. Students in the treatment group advanced from identifying system components (STH Level 1), to constructing relational and dynamic explanations (Level 2), and ultimately to applying systemic principles in novel contexts (Level 3). This pattern, along with ascending effect sizes across levels, suggests that the instructional strategy strengthened foundational knowledge while also supporting deeper integration and transfer.

These findings extend prior empirical work by Assaraf and Orion [7] and Riess and Mischo [6], who documented progressive coordination of elements, relations, and mechanisms. The present study specifies how this pattern unfolds within the domain of water state changes, and how targeted instructional supports can accelerate movement along the hierarchy. In particular, representational experiences—such as constructing concept maps, causal chains, and dynamic diagrams—played a central role in helping students integrate multiple variables and temporal processes. This reinforces the argument that systems thinking is fundamentally representational and relies on learners' ability to externalize and revise mental models.

A key contribution of this study is the articulation of developmental mechanisms that explain how students' systemic reasoning progressed. These mechanisms emerged from triangulated evidence across concept maps, interviews, and observations, rather than from predefined theoretical constructs. The first mechanism, causal density, reflects students' shift from identifying isolated elements to constructing densely connected causal networks. This reorganization allowed students to conceptualize phenomena as outcomes of interacting variables rather than linear sequences, consistent with mechanistic accounts of scientific reasoning [1].

The second mechanism, dynamic representational fluency, was evident in students' increased use of graphs, temporal markers, and energy-flow diagrams. These representations enabled learners to depict invisible processes—such as energy changes, humidity fluctuations, and temperature plateaus—and to view phenomena as evolving systems rather than static events, echoing principles in Kim's [5] Iceberg Model.

The third mechanism, hidden-variable awareness, emerged as students incorporated non-observable factors such as humidity, condensation nuclei, and energy balance into their explanations. This mechanism is particularly critical for STH Level 3, where

systemic application requires reasoning beyond perceptual cues. The prominence of hidden variables in later explanations signals a shift toward abstract and mechanism-driven reasoning.

Together, these mechanisms offer a fine-grained account of how systemic reasoning develops and illustrate the value of iterative scaffold design in shaping deeper understanding.

From a methodological perspective, the study demonstrates how DBR can operationalize complex theoretical constructs such as the STH model. Across three cycles of design, enactment, and analysis, the project identified specific learning challenges—such as limited relational reasoning or difficulty with non-observable variables—and addressed them through targeted refinements. This iterative process exemplifies the strength of DBR in bridging research and practice, aligning with the work of Brown [9], Collins [10], and Anderson and Shattuck [11].

The study also contributes to research on developmental readiness for systems thinking. Whereas prior work has primarily focused on older learners (e.g., [7]), the findings here show that younger students can engage in sophisticated systemic reasoning when instruction is appropriately scaffolded. This has implications for curriculum design: the six-phase strategy provides a feasible structure for integrating STH-aligned routines—identifying elements, mapping relations, visualizing dynamics, articulating mechanisms, and reasoning with hidden variables—into standard units.

The importance of representational scaffolds is particularly notable. Concept maps, flow diagrams, and data-based graphs supported students' transitions from descriptive accounts to mechanistic explanations. Systematic integration of these tools may therefore be essential for enabling learners to construct complex system models.

Although promising, the study has several limitations. It was conducted in a single school with two intact classes, which constrains the generalizability of findings. While pre-test equivalence mitigates threats to internal validity, future research should examine the strategy across diverse school contexts and grade levels. The focus on one scientific domain—water state changes—also limits transferability; additional work is needed to determine whether the strategy generalizes to other domains such as ecosystems, weather systems, or energy transfer.

The study relied primarily on concept maps, scenario tasks, and interviews, which capture key aspects of systemic reasoning but cannot fully represent its multidimensional nature. Future research might incorporate digital learning data, process-tracing methods, or eye-tracking to investigate how students coordinate representations during problem solving. Further, because the DBR process involved intensive collaboration with one teacher, additional research is needed to explore how professional development and teacher-led cycles can support broader implementation.

Overall, this study demonstrates that a theory-driven, iteratively refined instructional strategy can substantially enhance elementary students' systems thinking. By integrating the STH model with tailored scaffolds and representational supports, the project offers a feasible and effective approach for helping young learners interpret scientific phenomena through the lens of interaction, mechanism, and change. The findings contribute to the growing literature on systems thinking in science education and offer practical guidance for educators seeking to cultivate deeper scientific understanding in complex, dynamic worlds.

6. Conclusions

This study set out to design, implement, and evaluate a systems-thinking instructional strategy for elementary science education through a DBR approach grounded in the STH model. Across three iterative design cycles, the six-phase strategy was refined into a coherent and actionable framework that supported students in progressively deepening their understanding of system elements, relationships, dynamics, and underlying mechanisms. The integration of concept maps, scenario-based reasoning, and representational scaffolds played a critical role in helping students reorganize their ideas from event-based descriptions toward multi-variable, mechanism-based explanations of scientific phenomena.

The findings provide strong evidence that elementary students are capable of developing sophisticated forms of systems thinking when instruction is carefully scaffolded and developmentally appropriate. Quantitative gains across all STH levels, together with qualitative patterns of increasingly connected causal networks, growing attention to non-observable variables, and more flexible representational practices, demonstrate that the instructional strategy not only strengthened conceptual understanding but also fostered transferable systemic reasoning. These results challenge the assumption that systems thinking is too abstract for younger learners and highlight the value of integrating systemic reasoning within core scientific topics such as water state changes.

Beyond its immediate instructional contributions, the study advances understanding of how systems thinking emerges through iterative learning experiences. Analysis across the three DBR cycles shows that students' systemic reasoning developed through identifiable cognitive shifts, including the formation of denser causal connections, improved coordination of multiple representations, and greater incorporation of hidden variables into their explanations. These insights extend theoretical discussions surrounding the STH framework and underscore the utility of DBR for translating complex theoretical constructs into practical and teachable routines.

While the study was conducted in a single school and focused on one curriculum unit, the findings lay a foundation for broader application. Future research may explore how the six-phase strategy can be adapted to additional scientific domains, incorporated into teacher professional development, or investigated through longitudinal designs that trace systemic-reasoning development across grade levels. Overall, this study demonstrates that systems thinking can be meaningfully cultivated in elementary science and offers a replicable pathway for fostering deeper scientific literacy in an increasingly complex world.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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