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Technology-Enhanced Constructivist Instruction for Thermal Science Learning in Primary Education: Evidence from Two Independent Cohorts

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Abstract
Thermal phenomena are conceptually challenging for primary-school students because everyday interpretations of heat, temperature, heat transfer, and changes of state often differ from scientific explanations. This study examined a technology-enhanced constructivist instructional model for teaching thermal science to sixth-grade students across two independent cohorts. The study involved 88 students in Greece: 42 in the first cohort (21 experimental, 21 control) and 46 in the second (23 experimental, 23 control). The experimental groups participated in a 10-hour instructional sequence integrating concept mapping, the SEP digital simulation environment, inquiry-based worksheets, collaborative investigation, and Wordwall game-based activities, while the control groups followed conventional textbook-based instruction. Post-instructional performance was assessed across eight conceptual categories using a four-level ordinal coding scheme. Given the ordinal nature and non-normal distribution of the data, between-group comparisons were examined primarily through Mann–Whitney U tests. Significant differences favoring the experimental groups were replicated across both cohorts for thermometer identification, reasoning about heat transfer in an everyday context, changes of state, the distinction between evaporation and boiling, and thermal expansion and contraction. The distinction between evaporation and boiling showed particularly strong and consistent group differentiation across both cohorts. These findings support the educational value of integrating digital investigation, game-based activities, and constructivist inquiry within a coherent instructional sequence for primary thermal science education.

Keywords: Thermal Science Education, Heat and Temperature, Digital Simulations, Game-Based Learning, Constructivist Learning, Primary Education

1. Introduction

Heat and temperature are fundamental concepts in science education and are closely connected with everyday experiences and natural phenomena. Nevertheless, thermal phenomena remain conceptually challenging because students often interpret them through intuitive explanations that differ from scientific models. Research has documented persistent alternative conceptions concerning heat, temperature, heat transfer, and changes of state, including the tendency to use heat and temperature interchangeably, conceptualize heat as a substance contained in objects, and confuse evaporation with boiling [1, 2, 3]. These difficulties indicate that learning thermal science requires not only the acquisition of scientific terminology but also the reconstruction of students' prior explanations.

From a constructivist perspective, students' prior conceptions constitute an important starting point for science learning. Instruction should therefore provide opportunities for learners to articulate their ideas, make predictions, investigate phenomena, compare their expectations with evidence, and revise their explanations. Inquiry-based approaches are particularly appropriate for this purpose, while digital technologies can provide dynamic representations, controlled manipulation of variables, repeated experimentation, and immediate feedback. Previous research has shown that technology-supported inquiry can contribute to students' understanding of scientific phenomena, including changes of state and heat-related concepts [4, 6].

The present study examines a technology-enhanced constructivist instructional model for teaching thermal phenomena in primary education. The model integrates concept mapping, digital simulations, inquiry-based worksheets, collaborative investigation, and game-based activities within a coherent sequence of elicitation, prediction, observation, explanation, application, and reflection. Rather than treating digital tools as isolated resources, the instructional design assigns them complementary pedagogical roles aimed at supporting conceptual reconstruction across interconnected thermal phenomena.

1.1 Alternative Conceptions in Thermal Science Learning

Alternative conceptions concerning heat and temperature have been extensively documented across different educational levels [1, 2, 3]. Of particular relevance to primary education, students may regard heat and temperature as equivalent concepts, interpret "heat" or "cold" as substances entering or leaving objects, and have difficulty explaining heat transfer scientifically. More recent research has also documented difficulties in students' understanding of heat and temperature across primary, secondary, and university levels [14], while studies focusing on young children have highlighted the role of intuitive reasoning in their explanations of heat-transfer phenomena [13].

Misconceptions also occur in relation to changes of state. Evaporation may be associated exclusively with high temperatures, boiling may be regarded simply as an intensified form of evaporation, and students may expect the temperature of water to continue increasing during boiling [1, 2]. Research with elementary-school students has further shown that reasoning about changes in the state of water develops progressively across grade levels and may remain strongly dependent on macroscopic explanations [18]. Studies focusing specifically on evaporation have also demonstrated the importance of targeted instruction in supporting primary-school students' reasoning and argumentation about the phenomenon [19].

Further difficulties concern the interpretation of water vapor and condensation, the effect of the quantity of a liquid on boiling temperature, and the expansion and contraction of solids, liquids, and gases. Such ideas are important because they may appear internally consistent from the learner's everyday perspective and may therefore resist conventional explanation. Instruction aimed at conceptual reconstruction should consequently make students' initial ideas explicit and provide opportunities to test them against observable or simulated evidence. Conceptual-change-oriented approaches to heat and temperature have shown that active engagement with students' prior reasoning can support the restructuring of misconceptions [2, 7].

1.2 Technology-Enhanced and Inquiry-Based Learning of Thermal Phenomena

Digital technologies can support thermal science learning by providing opportunities for investigation, visualization, manipulation of variables, and repeated observation of processes that may be difficult to examine directly in the classroom. When embedded within inquiry-oriented instruction, these tools can enable students to formulate predictions, observe outcomes, compare evidence with their initial ideas, and progressively revise their explanations. Nicolaou *et al.* [4], for example, used Microcomputer-Based Laboratories within an inquiry-based activity sequence on melting and freezing with fourth-grade students, demonstrating the potential of technology-supported investigation for conceptual understanding and graphical interpretation. Research combining physical and virtual experimentation has similarly highlighted the value of digital representations when they are integrated into structured science-learning activities [5].

More recent approaches have incorporated augmented and mixed reality into the investigation of thermal phenomena. Strzys *et al.* [6] used mixed-reality representations in heat-conduction experiments, while Bakri *et al.* [8] incorporated augmented-reality video into worksheets for heat-related laboratory activities. Recent research has also examined structured teaching–learning sequences for heat transfer in primary education, emphasizing the role of inquiry in supporting students' understanding of conduction, convection, and radiation [9]. Technology-enhanced inquiry has additionally been applied to thermal expansion and contraction through mixed-reality environments [15]. Although some of these studies involved older learners or pre-service teachers, they illustrate how interactive digital representations can support the investigation of thermal processes that may otherwise be difficult to observe or represent.

Digital games can provide a complementary function within such instructional environments by offering opportunities for application, repetition, immediate feedback, and consolidation. Game-based approaches have been developed specifically for temperature and heat learning in elementary education [11]. More recent research has also integrated a digital educational game within inquiry-based science instruction with fourth-grade students, illustrating how game-based activities can operate as part of a broader inquiry-oriented learning sequence rather than as isolated technological resources [16]. This perspective is consistent with recent systematic evidence on serious games in STEM education, which highlights their potential to support learning and engagement while also emphasizing the importance of instructional design and implementation context [17].

Taken together, these studies suggest that the educational contribution of technology depends not simply on the use of individual digital tools but on the pedagogical purposes for which they are employed. In the present study, this principle informed the integration of concept mapping, the SEP digital environment, inquiry-based worksheets, collaborative investigation, and Wordwall activities within a coherent constructivist sequence. Digital investigation was used primarily to support prediction, observation, comparison, and conceptual reconstruction, whereas game-based activities provided additional opportunities for application, feedback, repetition, and consolidation. This integrated approach was intended to address several interconnected thermal concepts while maintaining alignment between students' conceptual difficulties, the learning objectives, and the instructional activities.

1.3 Research Gap and Contribution of the Present Study

Previous research has demonstrated the potential of inquiry-oriented and technology-enhanced approaches for supporting the teaching and learning of thermal phenomena. Studies have addressed individual areas such as melting and freezing [4], heat conduction and heat transfer [6, 9], thermal expansion and contraction [15], and changes of state and evaporation [18, 19]. Other research has focused on technological approaches, including augmented and mixed reality [6, 8, 15] and game-based learning [11, 16, 17]. Collectively, these studies provide valuable evidence for the use of inquiry and digital technologies in science education.

However, the existing literature remains heterogeneous in terms of the thermal concepts addressed, the technological tools employed, and the educational levels investigated. Many studies focus on a particular thermal phenomenon or a single type of digital resource, while some involve secondary-school, university, or pre-service teacher populations rather than primary-school students. Consequently, there remains a need to examine instructional designs that integrate multiple digital and inquiry-oriented resources within a coherent sequence specifically designed for primary education and addressing a broader range of interconnected thermal concepts.

The present study addresses this need by examining a technology-enhanced constructivist instructional model that integrates concept mapping, the SEP digital environment, inquiry-based worksheets, collaborative investigation, and Wordwall game-based activities. Rather than evaluating these resources as isolated tools, the instructional sequence assigns complementary pedagogical functions within a process of eliciting prior conceptions, prediction, investigation, observation, comparison, explanation, application, and reflection. The model addresses interconnected concepts including heat and temperature, temperature measurement, heat transfer, changes of state, evaporation and boiling, water vapor and condensation, and thermal expansion and contraction.

A further contribution of the study is its implementation across two independent cohorts, allowing the examination of whether similar patterns of post-instructional performance are observed across two consecutive implementations. Accordingly, the study focuses not only on between-group differences following instruction but also on the conceptual areas in which these patterns are replicated or vary across cohorts. In this way, the study contributes evidence concerning the use of an integrated technology-enhanced and inquiry-oriented instructional model for thermal science in primary education.

1.4 Research Questions

Based on the identified research gap and the objectives of the proposed instructional model, the present study examines students' post-instructional performance in thermal science following two different instructional approaches. Attention is given to differences between the experimental and control groups across the assessed conceptual areas and to the identification of thermal concepts in which students demonstrate comparatively stronger or weaker performance. Accordingly, the study was guided by the following research questions:

RQ1. Are there significant differences in post-instructional performance in thermal phenomena between students participating in the technology-enhanced constructivist instructional model and those receiving conventional textbook-based instruction?

RQ2. In which thermal concepts are the largest differences in post-instructional performance observed between the experimental and control groups?

RQ3. Which thermal concepts remain comparatively challenging for students following the instructional implementation?

2. Materials and Methods

2.1 Research Design

The study employed a quasi-experimental research design with non-equivalent experimental and control groups [12] to examine post-instructional performance in thermal phenomena following two different instructional approaches. The study involved two instructional conditions: an experimental group, which participated in the proposed technology-enhanced learning sequence, and a control group, which followed conventional textbook-based instruction.

The quasi-experimental design was implemented within authentic school settings, where students participated as members of their existing classes rather than being randomly assigned to experimental conditions. The instructional model was designed around constructivist and inquiry-oriented principles and emphasized the elicitation of students' initial conceptions, prediction, investigation, observation, comparison of evidence with prior ideas, explanation, and conceptual reconstruction.

Students in the experimental group engaged in an integrated sequence combining concept mapping, digital simulations, inquiry-based worksheets, collaborative activities, and educational digital games. These resources were not treated as isolated technological tools but were incorporated at different stages of the instructional process according to their pedagogical function. Simulations and inquiry activities were primarily used to support exploration and conceptual reconstruction, whereas game-based activities provided opportunities for application, immediate feedback, repetition, and consolidation.

The control group addressed the same core thermal concepts through the conventional instructional approach based on the official science curriculum and textbook. The principal difference between the two conditions therefore concerned the instructional approach and the learning resources used to support students' engagement with the scientific concepts.

The study focused on students' understanding of a broad range of interconnected thermal phenomena, including the distinction between heat and temperature, temperature measurement, mechanisms of heat transfer, thermal conductors and insulators, changes of state, evaporation and boiling, temperature during boiling, the relationship between the quantity of water and boiling temperature, water vapor and condensation, and thermal expansion and contraction.

2.2 Participants and Educational Context

The study involved 88 sixth-grade students attending primary schools in Greece across two consecutive school years. The first cohort comprised 42 students, with 21 students in the control group and 21 in the experimental group. The second cohort comprised 46 students, with 23 students in the control group and 23 in the experimental group. The control and experimental groups consisted of different students, and the two cohorts were analyzed separately to examine whether similar patterns of post-instructional performance were observed across the two implementations.

The thermal science unit was implemented in Grade 6 and addressed a broad range of thermal phenomena. The instructional content included heat and temperature, heat transfer, changes of state, boiling and evaporation, water vapor and condensation, and thermal expansion and contraction. These concepts were addressed as part of a coherent instructional sequence rather than as isolated activities.

In both cohorts, students in the experimental groups participated in the technology-enhanced constructivist instructional model, whereas students in the control groups followed conventional curriculum- and textbook-based instruction. The experimental and control groups addressed the same conceptual domain, allowing post-instructional performance to be compared within each cohort in relation to the instructional approach.

2.3 Learning Objectives and Alignment with Instructional Activities

The instructional model was designed around a set of clearly defined learning objectives addressing key concepts related to thermal phenomena. The objectives focused not only on students' understanding of heat, temperature, heat transfer, changes of state, boiling and evaporation, water vapor and condensation, and thermal expansion and contraction, but also on the identification and restructuring of common alternative conceptions associated with these phenomena. Each objective was directly linked to specific instructional activities and digital tools, including concept mapping, the SEP digital environment, inquiry-based worksheets, and Wordwall game-based activities. This alignment was intended to ensure coherence between the conceptual content, the instructional process, and the subsequent assessment of students' understanding. Table 1 presents the learning objectives and the corresponding instructional activities used during the implementation.

Table 1: Alignment of learning objectives with instructional activities and digital tools

Learning objective	*Conceptual focus*	*Instructional activities and digital tools*
O1. Heat and temperature	Distinction between heat and temperature and appropriate use of scientific terminology	Initial elicitation of students' ideas through concept mapping (Inspiration) and discussion of everyday thermal phenomena. Activities and Wordwall games focusing on the distinction between heat and temperature and the application of the concepts in different contexts.
O2. Thermometers and temperature measurement	Types of thermometers; temperature as a measurable physical quantity	Identification and discussion of different types of thermometers and their uses. Activities involving temperature measurement and interpretation of temperature values in the context of thermal phenomena.
O3. Heat transfer	Conduction, convection, and radiation	Investigation and discussion of the three mechanisms of heat transfer through examples from everyday life. Wordwall activities were used to distinguish between conduction, convection, and radiation and associate each mechanism with relevant phenomena.
O4. Thermal conductors and insulators	Thermal properties of materials; good and poor conductors of heat	Activities involving the classification of materials according to their thermal properties and discussion of the use of conductors and insulators in familiar objects and everyday applications.
O5. Changes of state	Melting, freezing, evaporation, boiling, condensation/liquefaction	Activities and worksheets focus on identifying and distinguishing changes of state and using the appropriate scientific terminology. Wordwall activities provided additional practice and consolidation.
O6. Boiling and evaporation	Differences between evaporation and boiling	Prediction and investigation activities focus on where and under what conditions evaporation and boiling occur. Students compared the two phenomena and applied the distinction through worksheets and digital activities.
O7. Temperature during boiling	Temperature changes during heating and constancy of temperature during boiling	Investigation using the SEP digital environment and accompanying worksheets. Students made predictions, observed temperature changes during heating, recorded results, and examined the behavior of temperature once boiling was reached.
O8. Quantity of liquid and boiling temperature	Relationship between quantity of water, heating time, and boiling temperature	Investigation using the SEP environment in which students examined the alternative conception that a larger quantity of water results in a higher boiling temperature. Predictions were compared with the observed results.
O9. Water vapor, bubbles, and condensation	Water vapor; bubbles during boiling; visible droplets and condensation	Prediction, observation, and discussion activities concerning the contents of bubbles during boiling and the distinction between invisible water vapor and the visible cloud of microscopic water droplets formed above boiling water.
O10. Thermal expansion and contraction	Expansion and contraction of solids, liquids, and gases	Activities addressing thermal expansion and contraction in the three states of matter, followed by application to everyday examples. Wordwall activities were used for practice, feedback, and consolidation.
O11. Application to everyday thermal phenomena	Application of thermal concepts to familiar situations	Discussion and interpretation of everyday phenomena and expressions, including "Close the window because the cold is coming in," the operation of radiators and hot-air balloons, and other examples involving heat transfer. Students applied the concepts developed during the instructional sequence to explain these situations scientifically.

In addition to the conceptual objectives presented in Table 1, the instructional sequence targeted the development of inquiry and collaborative learning skills. Students were encouraged to formulate predictions and hypotheses, make observations and measurements, systematically record results, compare their initial predictions with the observed evidence, identify discrepancies between their prior conceptions and the investigation outcomes, and formulate evidence-based conclusions. Collaborative work in small groups was incorporated throughout the activities, while digital tools and simulations supported investigation and game-based activities provided opportunities for application, feedback, and consolidation. Thus, the implementation addressed three interconnected dimensions: conceptual understanding, restructuring of alternative conceptions, and development of inquiry and collaborative skills.

2.4 Implementation Plan

The instructional implementation was structured according to a constructivist approach, in which students' prior conceptions were treated as the starting point for learning rather than as responses to be immediately classified as correct or incorrect. The instructional sequence was therefore designed to provide opportunities for students to express their existing ideas, test them through investigation, compare their predictions with observed evidence, and, where necessary, restructure their initial explanations. The implementation was organized into five successive and interconnected phases: orientation, elicitation of initial ideas, restructuring of alternative conceptions, application of new knowledge, and review and comparison.

During the orientation phase, students' interest was activated through questions and familiar situations related to heat, temperature, boiling, the operation of radiators, and other everyday thermal phenomena. A concept map developed with Inspiration was also used to introduce and connect central concepts, including heat, temperature, thermometers, conduction, convection, radiation, and thermal conductors and insulators. The purpose of the concept map was not to provide ready-made scientific explanations, but to establish a common conceptual framework within which students could express their existing knowledge and ideas. A concept map developed with Inspiration (Fig 1) was used to introduce and connect central concepts.

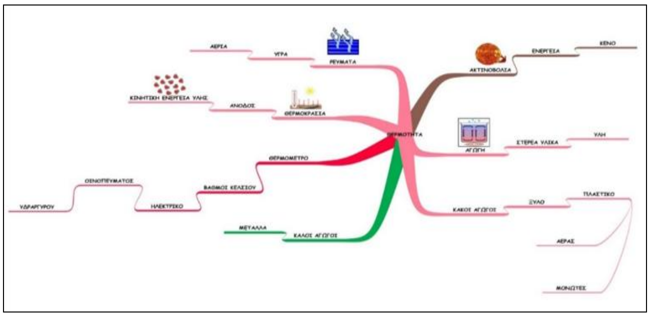

Fig 1: Concept map developed in inspiration and used during the orientation phase of the thermal science unit

The elicitation phase focused on students' prior conceptions and predictions. Before undertaking the corresponding investigative activities, students were asked to formulate predictions, respond to questions, and justify their reasoning. Attention was given to boiling. Students predicted how water temperature would change during continuous heating, whether the quantity of water would affect its boiling temperature, and what the bubbles appearing during boiling contained. These initial responses were recorded and subsequently used as reference points for comparison with the outcomes of the investigations. Table 2 presents eleven representative activities selected from the broader set of digital materials developed for the instructional implementation. For each activity, the table summarizes its content, its alignment with the learning objectives (O1–O11), and the main alternative conception or skill addressed. The activities were used during the application phase to provide students with opportunities to apply the concepts investigated during the preceding phases in different game-based contexts.

Table 2: Representative Wordwall game-based activities and their alignment with the learning objectives

Activity	*Content*	*Learning objective(s)*	*Targeted alternative conception/skill*
Maze – "What is heat?"	Heat, temperature, thermal expansion/contraction	O1, O10	Distinguishing heat from temperature
Concept classification	Evaporation, boiling, condensation, etc.	O5, O6	Distinguishing changes of state
Whack-a-Mole	Heat, temperature, thermal expansion	O1, O10	Examination of alternative conceptions
Hangman	Thermal expansion and contraction	O10	Connection with everyday applications
Fill-in-the-blanks	Melting, freezing, evaporation, condensation	O5	Appropriate use of scientific terminology
Quiz	Conduction	O3, O4	Thermal conductors and insulators
Random cards	Heat transfer	O3	Distinguishing mechanisms of heat transfer
Image quiz	Convection	O3, O11	Heat transfer through convection
Water cycle	Changes of state	O5, O9	Evaporation and condensation
Radiator operation	Convection in fluids	O3, O11	Scientific explanation of radiator operation
Random wheel	Radiation	O3	Heat transfer through radiation

The restructuring phase constituted the central investigative component of the implementation. Working in small groups, students used the SEP digital environment together with accompanying inquiry-based worksheets to conduct virtual experiments and examine their initial predictions. The activities followed a prediction–observation–comparison–interpretation sequence. Students first recorded what they expected to occur, performed the virtual experiment, observed the resulting changes, recorded measurements, and compared the observed outcomes with their original predictions. In the activities concerning boiling, repeated experimentation and observation of temperature changes enabled students to examine conceptions such as the belief that water temperature continues to increase during boiling or that a larger quantity of water results in a higher boiling temperature. Discrepancies between prediction and observation were used as starting points for discussion and reconsideration of students' initial explanations. Thus, digital experiments functioned as tools for inquiry and conceptual restructuring rather than simply as demonstrations of thermal phenomena. Working in small groups, students used the SEP digital environment (Fig 2) together with accompanying inquiry-based worksheets.

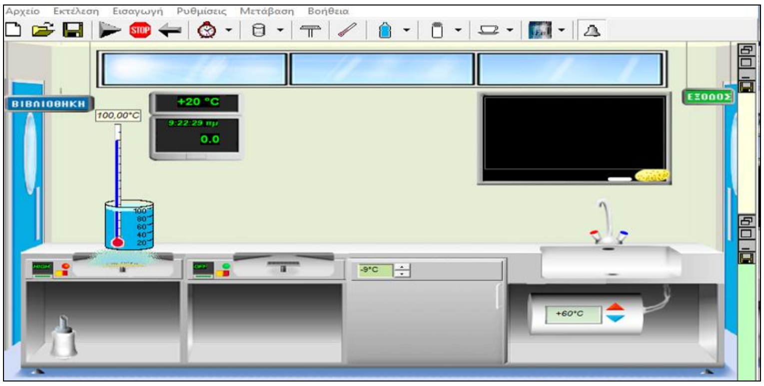

Fig 2: Sep digital environment

During the application phase, students applied the concepts developed during the investigative activities through game-based tasks created in Wordwall. These included mazes, classification activities, quizzes, matching tasks, fill-in-the-blank activities, hangman, random-wheel activities, and tasks incorporating images and diagrams. Their content was aligned with specific learning objectives and alternative conceptions addressed during the preceding phases. Immediate feedback enabled students to check their responses and repeat activities, when necessary, while collaborative completion of the games encouraged discussion and justification of answers within each group. During the application phase, students applied the concepts through game-based tasks created in Wordwall (Fig 3).

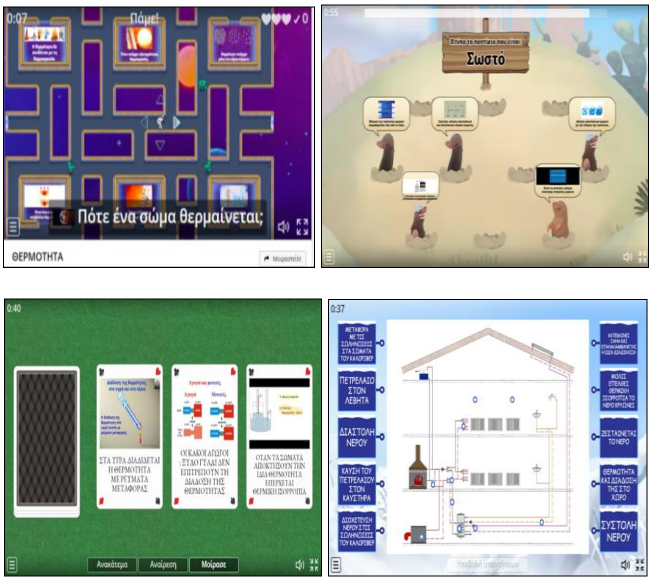

Fig 3: Examples of Wordwall game

In the final review and comparison phase, students revisited the predictions and ideas recorded before the investigative activities. Through discussion, review, and comparison of their initial and subsequent explanations, they were encouraged to identify which ideas had been confirmed, which had changed, and how the same thermal phenomena could now be interpreted using more scientifically appropriate concepts. This phase also introduced a metacognitive dimension by encouraging students to reflect on changes in their own reasoning throughout the instructional process.

Throughout the implementation, the teacher assumed a primarily facilitative and supportive role, posing questions, encouraging students to justify their predictions, supporting group collaboration, and providing guidance when required during the inquiry process. Students, in contrast, assumed an active role by formulating hypotheses, interacting with the digital environments, conducting virtual experiments, recording and comparing data, discussing alternative explanations, and drawing conclusions from their observations. Small-group collaboration was maintained throughout the instructional sequence.

Overall, the implementation combined constructivist, inquiry-based, collaborative, and game-based learning within a coherent instructional framework. Concept mapping was used to activate and elicit prior knowledge; the SEP digital environment and inquiry worksheets supported investigation and conceptual restructuring; and Wordwall activities supported application, feedback, and consolidation of the newly developed knowledge.

2.5 Organization of the Instructional Sequence

The thermal science instructional sequence comprised 10 teaching hours, in accordance with the instructional time allocated to the corresponding units in the Teacher's Book. The sequence was organized into eight thematic components, progressing from temperature measurement and the distinction between temperature and heat to changes of state and thermal expansion and contraction in solids, liquids, and gases. Table 3 presents the duration, thematic focus, corresponding learning objectives, and instructional materials associated with each component of the sequence.

Table 3: Organization of the Thermal Science Instructional Sequence

Duration (hours)	Topic	Learning objectives	Digital materials and activities
1	Thermometers and temperature measurement	Students recognize the limitations of sensory temperature estimation, identify basic thermometer types, and understand temperature measurement.	Concept mapping; instructional activities; digital materials
2	Temperature and heat	Students distinguish between temperature and heat and recognize heat as energy transferred because of a temperature difference.	Inspiration concept mapping; SEP activities; inquiry worksheets; Wordwall
2	Melting and freezing	Students explain melting and freezing and recognize that temperature remains constant during a change of state under the conditions investigated.	SEP activities; inquiry worksheets; Wordwall
1	Evaporation and condensation	Students distinguish evaporation and condensation and relate these processes to energy transfer.	Digital activities; inquiry worksheets; Wordwall
1	Boiling	Students distinguish boiling from evaporation and investigate the behavior of temperature during boiling.	SEP digital environment; inquiry worksheets; Wordwall
1	Heating and cooling solids	Students recognize thermal expansion and contraction in solids and relate these phenomena to everyday applications.	Inquiry activities; Wordwall
1	Heating and cooling liquids	Students investigate thermal expansion and contraction in liquids and connect these phenomena with thermometer operation and everyday applications.	Inquiry activities; Wordwall
1	Heating and cooling gases	Students investigate thermal expansion and contraction in gases and apply their understanding to familiar phenomena.	Inquiry activities; Wordwall

As shown in Table 3, the thermal science instructional sequence comprised 10 teaching hours and progressed from temperature measurement and the distinction between heat and temperature to changes of state and thermal expansion and contraction. The sequence devoted particular attention to conceptually demanding phenomena, including the distinction between heat and temperature, melting and freezing, evaporation and condensation, and boiling. Digital and inquiry-based activities were integrated throughout the sequence to support the elicitation, investigation, and restructuring of students' initial conceptions, while game-based activities provided opportunities for application, feedback, and consolidation.

2.6 Data Analysis

Statistical analyses were performed using jamovi, version 2.7.38. The quantitative analysis was based on students' responses to the final assessment administered following completion of the thermal science unit. Responses were classified according to a four-level coding scheme: 1 = correct, 2 = partially correct, 3 = incorrect, and 4 = no response. Thus, lower numerical values indicated more accurate performance. Descriptive statistics, including means and standard deviations, were obtained for each of the eight assessed conceptual categories separately for the experimental and control groups.

Analyses were conducted independently for the two cohorts because the participants in the two implementations were different students. The first cohort comprised 42 students (21 experimental and 21 control), whereas the second cohort comprised 46 students (23 experimental and 23 control). No observations were therefore treated as repeated or matched across groups or cohorts.

Between-group differences in post-instructional performance were initially examined using independent samples t-tests. The homogeneity-of-variance assumption was evaluated using Levene's test, and Welch's correction was considered when equal variances could not be assumed. Cohen's d was calculated to describe the standardized magnitude of the between-group differences.

Because the response variable was based on an ordinal four-category coding scheme and Shapiro–Wilk tests indicated departures from normality across the assessed categories, the comparisons were also examined using the Mann–Whitney U test. Rank-biserial correlation (rrb) was used as the corresponding non-parametric effect-size measure. The non-parametric results were considered particularly informative given the ordinal nature of the coding scheme and the relatively small group sizes. All statistical tests were two-tailed, with the significance level set at $p < .05$.

Finally, findings from the two cohorts were examined descriptively to determine whether similar patterns of between-group differences were observed across the two independent implementations. This comparison was intended to assess the replication of result patterns across cohorts rather than change over time, as the two cohorts consisted of different students.

2.7 Ethical Considerations

The research protocol received ethical approval from the Ethics and Deontology Committee of the Department of Computer Science and Biomedical Informatics, University of Thessaly, on 18 January 2022. The approval covered research on the development and implementation of new approaches to teaching physics-related topics to primary school students using simulations, digital games, cartoons, and related digital educational tools.

Prior to participation, written informed consent was obtained from the students' parents or legal guardians. Participation was voluntary, and confidentiality and anonymity were maintained throughout data collection, coding, and analysis. No personally identifying information was included in the research dataset, and all findings are reported at group level.

3. Results and Discussion

3.1 Statistical Analysis

Post-instructional performance was compared between the experimental and control groups separately for each school year. The first-year cohort consisted of 42 students (21 control and 21 experimental), whereas the second-year cohort consisted of 46 students (23 control and 23 experimental).

Student responses were coded using an ordinal four-level scoring scheme, with lower scores representing better performance: 1 = correct response, 2 = partially correct response, 3 = incorrect response, and 4 = no response. Group differences were initially examined using independent samples t-tests, with Welch's correction considered when the assumption of homogeneity of variance was violated. Because the response variable was ordinal and the Shapiro–Wilk tests indicated significant departures from normality across all eight conceptual categories in both cohorts, Mann–Whitney U tests were additionally used as a non-parametric comparison of the two independent groups. In the first cohort, all Shapiro–Wilk tests were significant at $p < .001$, while violations of homogeneity of variance were identified for Q1, Q2, and Q8. In the second cohort, all eight variables again departed significantly from normality ($p < .001$), while Levene's test indicated unequal variances for Q1, Q6, Q7, and Q8.

Given these distributional characteristics and the ordinal nature of the coding scheme, the Mann–Whitney U results were used as an important complementary basis for interpreting group differences, alongside the parametric results.

3.2 First-Year Post-Test Results

Post-test performance was first compared between the control and experimental groups in the first cohort. Each group consisted of 21 students. Because responses were coded on an ordinal four-level scale and the assumption of normality was violated across all eight conceptual categories, Mann–Whitney U tests were used as a non-parametric comparison of the two independent groups. Descriptive statistics are also reported to illustrate the performance pattern across the assessed thermal concepts. Table 4 presents the first year between-group results.

Table 4: First-year post-test comparison between the control and experimental groups

Conceptual category	*Control M (SD)*	*Experimental M (SD)*	*U*	*p*	*Rank-biserial r*
Types of thermometers	2.10 (1.30)	1.00 (0.00)	105.00	<.001	−.524
Temperature–thermal energy	1.95 (0.74)	2.00 (0.00)	210.00	.744	.048
Heat	3.19 (1.17)	1.29 (0.90)	68.00	<.001	−.692
"Close the window because the cold is coming in"	2.81 (0.87)	1.67 (1.11)	86.00	<.001	−.610
Melting–freezing–condensation/liquefaction	2.29 (0.90)	1.76 (0.89)	142.00	.025	−.356
Condensation–evaporation–boiling–liquefaction	2.43 (1.21)	1.71 (1.31)	159.00	.085	−.279
Difference between evaporation and boiling	3.14 (0.57)	1.29 (0.90)	37.00	<.001	−.832
Thermal expansion and contraction of solids, liquids, and gases	2.38 (1.28)	1.14 (0.66)	108.50	<.001	−.508

As shown in Table 4, statistically significant differences between the experimental and control groups were identified in six of the eight conceptual categories. Significant differences were observed for types of thermometers (*Q1, U = 105.00, p < .001*), heat (*Q3, U = 68.00, p < .001*), the everyday conception that "cold comes in" through an open window (*Q4, U = 86.00, p < .001*), changes of state (*Q5, U = 142.00, p = .025*), the distinction between evaporation and boiling (*Q7, U = 37.00, p < .001*), and thermal expansion and contraction (*Q8, U = 108.50, p < .001*). In each of these categories, the experimental group showed lower mean scores, indicating better post-test performance under the response-coding scheme.

The strongest group differentiation was observed for the distinction between evaporation and boiling (Q7), which produced the largest absolute rank-biserial correlation (*r = −.832*). By contrast, no statistically significant differences were identified for temperature–thermal energy (*Q2, U = 210.00, p = .744*) or for condensation–evaporation–boiling–liquefaction (*Q6, U = 159.00, p = .085*).

3.3 Second-Year Post-Test Results

The same between-group analysis was conducted for the second cohort, comprising 23 students in the control group and 23 students in the experimental group. As in the first cohort, significant departures from normality were identified across all eight conceptual categories. Mann–Whitney U tests were therefore used to complement the descriptive comparison of post-test performance between the two independent groups. Table 5 presents the second-year results.

Table 5: Second-year post-test comparison between the control and experimental groups

Conceptual category	*Control M (SD)*	*Experimental M (SD)*	*U*	*p*	*Rank-biserial r*
Types of thermometers	1.78 (1.09)	1.00 (0.00)	161.00	.001	−.391
Temperature–thermal energy	3.17 (0.58)	1.35 (0.49)	8.00	<.001	−.970
Heat	1.65 (0.98)	1.30 (0.88)	200.50	.070	−.242
"Close the window because the cold is coming in"	3.22 (0.60)	1.48 (0.95)	55.50	<.001	−.790
Melting–freezing–condensation/liquefaction	2.57 (0.66)	1.35 (0.94)	60.50	<.001	−.771
Condensation–evaporation–boiling–liquefaction	2.96 (0.71)	1.78 (1.28)	117.50	<.001	−.556
Difference between evaporation and boiling	3.17 (0.58)	1.52 (0.85)	49.50	<.001	−.813
Thermal expansion and contraction of solids, liquids, and gases	2.35 (0.89)	1.22 (0.67)	88.50	<.001	−.665

The second-year findings showed statistically significant differences between the experimental and control groups in seven of the eight conceptual categories. Significant differences were found for types of thermometers (*Q1, U = 161.00, p = .001)*, temperature–thermal energy *(Q2, U = 8.00, p < .001),* the everyday conception that "cold comes in" through an open window *(Q4, U = 55.50, p < .001),* changes of state *(Q5, U = 60.50, p < .001),* condensation–evaporation–boiling–liquefaction *(Q6, U = 117.50, p < .001*), the distinction between evaporation and boiling *(Q7, U = 49.50, p < .001)*, and thermal expansion and contraction *(Q8, U = 88.50, p < .001*). In all seven statistically significant categories, lower mean scores were observed in the experimental group, indicating better post-test performance.

The largest absolute rank-biserial correlation was observed for temperature–thermal energy *(Q2, r = −.970),* followed by the distinction between evaporation and boiling *(Q7, r = −.813)* and the everyday conception concerning the entry of "cold" through an open window *(Q4, r = −.790). Heat (Q3)* was the only category for which the between-group difference did not reach statistical significance *(U = 200.50, p = .070)*.

3.4 Comparison Across the Two Cohorts

Across the two independent cohorts, a broad consistent pattern of post-test differences was observed. Five conceptual categories—types of thermometers (Q1), the everyday conception concerning the entry of "cold" (Q4), changes of state (Q5), the distinction between evaporation and boiling (Q7), and thermal expansion and contraction (Q8)—showed statistically significant differences between the experimental and control groups in both years. The distinction between evaporation and boiling was particularly consistent, with large rank-biserial correlations in both the first (r = −.832) and second (r = −.813) cohorts. In contrast, some findings varied across cohorts: temperature–thermal energy (Q2) and condensation–evaporation–boiling–liquefaction (Q6) were significant only in the second year, whereas heat (Q3) was significant only in the first year. These patterns indicate replication across several conceptual areas while also revealing cohort-specific variation in particular thermal concepts.

3.5 Discussion of the Findings

The findings across the two independent cohorts indicate a broadly consistent pattern of better post-instructional performance among students who participated in the technology-enhanced constructivist instructional sequence. Statistically significant between-group differences were replicated in both cohorts for the identification of thermometer types (Q1), reasoning about the everyday statement that "cold comes in" through an open window (Q4), changes of state (Q5), the distinction between evaporation and boiling (Q7), and thermal expansion and contraction (Q8). Particularly noteworthy was the distinction between evaporation and boiling, which showed the strongest group differentiation in the first cohort (r = −.832) and one of the strongest in the second cohort (r = −.813). The recurrence of significant differences across five conceptual categories and two independent implementations suggests a consistent pattern of better post-instructional performance in the experimental groups. However, because the study compared independent groups following instruction, these findings should be interpreted as differences in post-instructional performance rather than as direct measures of individual learning gains.

These findings are particularly relevant in view of the persistent conceptual difficulties associated with thermal phenomena. Previous research has shown that students may use heat and temperature interchangeably, conceptualize heat as a substance contained in or transferred between objects, and rely on everyday intuitive explanations rather than scientific models of energy transfer [1, 2, 3]. More recent evidence has also documented difficulties in understanding heat and temperature across different educational levels [14]. The persistence of such conceptions suggests that presenting scientific definitions alone may be insufficient and that instruction should provide opportunities for students to express, examine, and reconsider their existing explanatory models. In the present instructional sequence, concept mapping and discussion of everyday thermal phenomena were used to elicit students' initial ideas, while subsequent investigation, observation, discussion, and application provided opportunities to reconsider these ideas in relation to scientific evidence.

The replicated findings for the everyday statement that "cold comes in" through an open window (Q4) are particularly relevant to this process. Significant differences between the experimental and control groups were observed in both cohorts. The item required students to move beyond an everyday linguistic expression and interpret the phenomenon in terms of heat transfer. Research focusing specifically on young children's ideas about heat-transfer phenomena has highlighted the role of intuitive and experience-based reasoning in their explanations [13]. Recent work in primary education has also emphasized the value of structured inquiry-oriented teaching–learning sequences for developing understanding of heat-transfer mechanisms [9]. The Q4 findings are therefore consistent with an instructional approach in which familiar everyday situations are used to make students' initial explanations explicit and provide contexts in which intuitive and scientific interpretations can be compared.

Changes of state constitute another important area of differentiation. Q5 showed statistically significant between-group differences in both cohorts, although the magnitude of the difference was smaller in the first cohort than in the second. Q6, which incorporated condensation, evaporation, boiling, and liquefaction, showed a significant difference only in the second cohort. Research with elementary-school students indicates that reasoning about changes in the state of water develops progressively and that students may rely strongly on macroscopic features when explaining these phenomena [18]. This is particularly relevant because understanding changes of state requires learners to relate directly observable phenomena to processes and relationships that are not always immediately visible. The variation observed for Q6 between the two cohorts further suggests that different aspects of state change may not be equally accessible to students or equally differentiated between instructional conditions.

The distinction between evaporation and boiling (Q7) deserves particular attention because it produced one of the strongest and most consistent findings of the study. The experimental group demonstrated better post-instructional performance in both cohorts, with large rank-biserial correlations (r = −.832 and −.813). Within the instructional sequence, students were required to distinguish evaporation at the free surface of a liquid from boiling throughout the liquid under appropriate conditions. They also investigated temperature during boiling and considered bubbles, water vapor, and condensation. These activities directly addressed conceptual distinctions that can be obscured when students interpret thermal phenomena primarily through everyday observation. Previous research with elementary-school students has highlighted the developmental complexity of reasoning about changes in the state of water [18], while research specifically addressing evaporation in primary education has emphasized the value of engaging students actively in reasoning and argumentation about the phenomenon [19]. The replicated Q7 findings are therefore consistent with the view that explicit conceptual differentiation, combined with opportunities for prediction, investigation, discussion, and application, is particularly relevant when teaching closely related thermal processes.

The digital investigative component of the instructional model was especially relevant to these thermal phenomena. Processes involving heating, boiling, temperature change, and state transitions can be difficult to investigate repeatedly in primary-school settings, while some aspects of thermal processes are not directly observable. Digital environments can complement physical experience by enabling learners to manipulate variables, repeat investigations, and examine relationships under controlled conditions. Previous research has demonstrated the educational potential of computer-supported and virtual experimentation for thermal science [4, 5], while augmented- and mixed-reality approaches have extended these possibilities by providing additional representations of heat-related processes [6, 8]. In the present study, the SEP environment was not used merely as a visualization tool but as part of an inquiry-oriented process supported by worksheets requiring prediction, observation, comparison, and conclusion drawing. Nevertheless, the current design does not allow the contribution of SEP to be separated from the other components of the instructional sequence.

Thermal expansion and contraction (Q8) provided another replicated finding, with statistically significant differences between-groups in both cohorts. The instructional sequence addressed expansion and contraction across solids, liquids, and gases and connected these phenomena with observable applications. This allowed students to encounter the same underlying thermal principle in different contexts rather than as an isolated scientific fact. Technology-enhanced inquiry has also been used to investigate expansion–contraction phenomena through interactive representations [15]. Although that research involved pre-service teachers rather than primary-school pupils, it illustrates the potential of inquiry-oriented digital environments for representing and investigating thermal processes that may otherwise be difficult to conceptualize. The replicated Q8 findings in the present study extend this discussion to an integrated instructional context involving primary-school students.

The game-based component served a different but complementary pedagogical function. Wordwall activities were used to provide opportunities for application, immediate feedback, repetition, and consolidation across concepts including heat and temperature, changes of state, heat transfer, and thermal expansion and contraction. This role is consistent with the broader view that digital games are most educationally meaningful when they are embedded within purposeful instructional sequences rather than used as isolated motivational activities. Recent research with fourth-grade students has integrated a digital educational game into inquiry-based science instruction [16], while systematic evidence concerning serious games in STEM education points to their potential to support learning and engagement when appropriately aligned with instructional objectives and contexts [17]. In the present study, therefore, the Wordwall activities should be interpreted as one component of the broader constructivist sequence rather than as an independent intervention.

Not all conceptual categories, however, showed the same pattern across the two cohorts. Heat (Q3) showed a statistically significant between-group difference in the first cohort but not in the second, whereas temperature–thermal energy (Q2) and condensation–evaporation–boiling–liquefaction (Q6) showed significant differences only in the second cohort. Particularly striking was the second-cohort result for temperature–thermal energy (Q2), which produced the largest absolute rank-biserial correlation in that cohort ($r = -.970$), despite the absence of a significant difference for the corresponding category in the first cohort ($p = .744$). These findings demonstrate that the pattern of post-instructional performance was not uniform across all thermal concepts or groups of students. They also caution against interpreting a strong result from one cohort as evidence of a consistently replicated difference. The cohort-specific patterns for Q2 and Q3 are especially relevant given the broader literature documenting persistent difficulties in differentiating heat, temperature, and related energy concepts [1, 2, 3, 14].

The findings should therefore be interpreted in terms of both replication and variation. Five of the eight assessed conceptual categories showed statistically significant differences in the same direction across both independent cohorts, providing evidence of a recurring pattern associated with the instructional model. At the same time, the cohort-specific results for Q2, Q3, and Q6 indicate that the same pattern did not occur uniformly across every thermal concept. Because the cohorts consisted of different students and no formal statistical comparison between cohorts was conducted, these differences should not be interpreted as improvement or decline from one year to the next. Rather, they demonstrate the importance of examining the consistency of instructional findings across independent implementations.

Taken together, the results suggest that the educational value of the instructional model lies not in the mere presence of digital technology but in the pedagogical integration of different resources with clearly defined conceptual objectives. Concept mapping was used to elicit students' prior ideas; the SEP environment and inquiry worksheets supported prediction, investigation, observation, comparison, and evidence-based reasoning; and Wordwall activities provided opportunities for application, feedback, repetition, and consolidation. This integrated structure is consistent with contemporary research emphasizing inquiry-oriented approaches to thermal science [9], technology-supported representations and investigation of thermal phenomena [15], and the integration of digital games within inquiry and STEM learning [16, 17]. At the same time, because the study evaluated the complete instructional sequence, the contribution of individual components cannot be isolated. The findings therefore support the integrated instructional model rather than establishing the independent effectiveness of SEP, Wordwall, concept mapping, or any other single instructional resource.

4. Conclusion

This study examined a technology-enhanced instructional approach for teaching thermal science concepts to primary school students across two independent cohorts. The findings showed a broad consistent pattern of better post-instructional performance among students who participated in the integrated instructional sequence compared with those who followed conventional textbook-based instruction. Across both cohorts, significant between-group differences were consistently observed in thermometer identification, the interpretation of heat transfer in an everyday context, changes of state, the distinction between evaporation and boiling, and thermal expansion and contraction. The particularly strong and replicated findings for evaporation and boiling indicate the importance of providing students with opportunities to investigate and differentiate closely related thermal phenomena rather than relying solely on verbal explanations.

A central feature of the instructional approach was the systematic alignment between learning objectives and instructional activities. Concept mapping was used to elicit students' initial ideas, the SEP digital environment supported the investigation of thermal phenomena, inquiry worksheets encouraged prediction, observation, comparison, and evidence-based reasoning, and Wordwall games provided opportunities for application, immediate feedback, repetition, and consolidation. This combination was particularly appropriate for thermal science, where students are required to reason about processes that are often abstract or not directly observable and where some experimental procedures involving heating or boiling require careful management in primary classrooms.

The findings also showed that performance patterns were not identical across all conceptual categories or cohorts. Differences concerning heat, temperature–thermal energy relationships, and some changes of state varied between the two implementations, highlighting the persistent conceptual difficulty of thermal phenomena and the need for continued instructional attention to these areas. Moreover, because the study evaluated an integrated instructional model, the contribution of individual components such as the SEP environment or Wordwall games cannot be isolated.

Overall, the two-cohort findings provide evidence supporting the educational value of integrating digital investigation, game-based activities, and constructivist inquiry into primary thermal science instruction. Rather than functioning as supplementary technological resources, the digital tools were embedded within a coherent sequence designed to connect students' prior conceptions with investigation, feedback, and application. Future research with larger samples, additional educational settings, and delayed assessments could further examine the consistency and longer-term retention of these learning outcomes and clarify the contribution of individual components of the instructional model.

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