

Organizing energy instruction around the work and energy relation to support knowledge integration in secondary physics

Zihao Yang and Lei Bao^{*}

School of Biological Science and Medical Engineering, Research Center for Learning Science, Key Laboratory of Child Development and Learning Science, Ministry of Education, Southeast University, Nanjing 211189, China



(Received 13 May 2026; accepted 28 July 2026; published 24 August 2026)

Energy is a central idea in physics, but students often learn energy as a set of loosely connected terms, equations, and conservation statements rather than as an integrated explanatory framework. Prior physics education research (PER) has shown that students have persistent difficulty identifying appropriate systems, tracing energy changes across systems and forms, and applying energy conservation in unfamiliar contexts. Drawing on the knowledge integration perspective and on research on systems-based energy reasoning, this study developed a conceptual framework for a ninth-grade energy unit in which the work and energy relation served as the central organizing relation linking energy change, energy conservation, and contextualized problem solving. We implemented a conceptual-framework-based instructional intervention and compared it with regular textbook-sequence instruction in a quasi-experimental study involving two intact ninth-grade classes in China. Both groups studied the same curriculum content for the same amount of instructional time and were taught by the same teacher. Analysis of covariance showed that, after controlling for pretest performance, the intervention group significantly outperformed the control group on the overall post-test score and on the three conceptual categories of energy change, energy conservation, and the work and energy relation. Statistical mediation analyses further showed that the intervention group's post-test advantage was associated with students' performance on the work and energy relation. In the post-test mediation model, this indirect association was larger for atypical context performance than for typical context performance. These findings provide classroom-based evidence that reorganizing energy instruction around a core conceptual relation can support students' integrated understanding and application of energy ideas. The study contributes to PER by extending conceptual-framework-based instruction to a broader secondary energy unit and by clarifying how a work-centered organization may support reasoning beyond familiar surface features.

DOI: [10.1103/wjyg-1hmx](https://doi.org/10.1103/wjyg-1hmx)

I. INTRODUCTION

Energy is one of the most important organizing ideas in physics and in science education more broadly. It provides a way to reason across mechanics, thermodynamics, electricity, waves, chemistry, biology, Earth science, and engineering, and it is widely treated as a core concept in curriculum standards and learning progression research [1–6]. At the same time, energy is difficult for students to learn in a deep and transferable way. Students may be able to name energy forms, recite the law of conservation of energy, or apply familiar formulas in textbook

problems, yet still have difficulty explaining where energy is located, how it changes, why it changes, and how conservation should be applied when system boundaries are not obvious [3,7–14].

Physics education research (PER) has documented several persistent challenges in students' learning of energy. Students often treat energy form labels as the main substance of energy understanding, rather than using those labels as resources for explaining physical processes [3,5,6]. Students also have difficulty distinguishing between energy transfer across system boundaries and energy transformation among forms [3,4,15]. In dissipative processes, students may say that energy is “lost” or “used up,” rather than tracking how energy spreads into a larger system and becomes less available for macroscopic use [13,14,16]. Students' reasoning about work and energy is also fragile. Even after instruction, many students have difficulty applying the work and energy relation to extended systems, nonstandard force situations, and problems in which the relevant system must be chosen explicitly [9–12]. These

^{*}Contact author: lei.bao@outlook.com

Published by the American Physical Society under the terms of the *Creative Commons Attribution 4.0 International license*. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

findings suggest that the challenge is not simply that students lack individual pieces of energy knowledge. Rather, students often lack a coherent structure that connects energy forms, systems, interactions, energy transfer, energy transformation, and conservation.

This problem is closely related to a broader finding in PER and learning sciences research: students' success on familiar quantitative problems does not necessarily imply deep conceptual understanding [17,18]. Traditional problem solving can encourage students to associate surface features with known equations rather than to construct an explanatory representation of the physical situation [19,20]. Expert physicists tend to categorize problems according to deep principles, whereas novices tend to focus on surface features such as objects, diagrams, and familiar wording [19,21]. For energy learning, this means that students may solve familiar conservation of mechanical energy problems but fail when the same underlying principle appears in a less familiar context, when friction or thermal energy is involved, or when system boundaries are not specified.

The knowledge integration perspective provides a useful way to frame this problem. From this perspective, learning involves eliciting students' existing ideas, adding new normative ideas, distinguishing among competing ideas, and connecting ideas into a coherent and useful knowledge system [22,23]. Deep understanding is therefore not defined only by the number of concepts that students know. It also depends on how those concepts are connected and whether students can use those connections to explain and solve problems in varied contexts. This perspective has been used to study students' learning of energy [6,23], and it has also motivated the development of conceptual-framework models in physics learning. Such models specify the central ideas, supporting concepts, and reasoning pathways within a particular domain, thereby making the structure of knowledge integration more explicit [24–30].

Recent work on conceptual-framework assessment and instruction has shown that such models can support both measurement and instructional design. Conceptual-framework-based studies have examined topics such as momentum, simple electric circuits, Newton's third law, mechanical waves, work and mechanical energy, measurement uncertainty, and interdisciplinary electrochemical concepts [24–30]. Instructional studies based on these frameworks suggest that reorganizing instruction around central conceptual relations can improve students' knowledge integration and support more coherent reasoning [31–34]. The present study builds on this line of work and applies it to a secondary school energy unit.

Energy learning has also been examined through learning progressions, systems approaches, energy tracking representations, and fields-based instruction [3–6,15,35–40]. These studies emphasize that students need to identify

systems, track energy across boundaries, account for dissipation, and connect energy conservation with physical mechanisms. In this literature, work has a productive but bounded role. Work is not the only way that energy is transferred, and energy processes such as heating and radiation require additional conceptual resources. Nevertheless, for mechanics-rich contexts and for the secondary energy unit examined in the present study, the relation between work and changes in energy can provide a powerful bridge between interactions and energy accounting [8–12,41,42]. When students analyze which system is chosen, which forces act across or within that system, and how work is associated with changes in kinetic, potential, or internal energy, energy conservation can become more than a memorized statement.

The present study therefore focuses on a central instructional question. If students' energy knowledge is often fragmented, can instruction improve their learning by reorganizing the same curriculum content around a core relation that connects interactions, energy changes, and conservation? We address this question by developing an energy conceptual framework for a ninth-grade unit in which the work and energy relation serves as the central organizing relation. This choice is motivated by prior research showing that work and energy reasoning is difficult for students [9–12], that systems and energy transfer must be made explicit [3,13–16,35–40], and that conceptual-framework-based instruction can promote knowledge integration [31–34]. The framework used here does not claim that work alone explains all energy phenomena. Rather, it treats the work and energy relation as a productive organizing relation for the targeted instructional domain, especially for helping students connect energy change, energy conservation, and contextualized reasoning.

The study contributes to PER in three ways. First, it extends conceptual-framework-based instruction from a narrower focus on work and mechanical energy to a broader secondary energy unit that includes energy change, conservation, directionality, and efficiency. Second, it provides classroom-based evidence from an intact class setting in which the intervention and comparison conditions covered the same curriculum content and used the same instructional time. Third, it examines not only whether the intervention improved overall performance but also whether the intervention advantage was statistically associated with students' performance on the work and energy relation, especially in contexts that were less familiar and therefore more likely to require reasoning beyond surface cues.

The study was guided by two research questions.

RQ1: To what extent does conceptual-framework-based instruction improve students' understanding and application of energy-related knowledge, compared with regular textbook-sequence instruction?

RQ2: To what extent is the intervention group's post-test advantage statistically associated with students' performance on the work and energy relation, and is this association more pronounced for atypical context performance than for typical context performance?

II. ENERGY CONCEPTUAL FRAMEWORK

This section describes the energy conceptual framework used to design the intervention. The framework was developed by synthesizing the knowledge integration perspective, prior conceptual-framework studies in physics, and PER literature on energy, work, systems, dissipation, and conservation.

Energy learning is often organized in curricula around several content categories, including energy forms, energy transfer, energy transformation, energy dissipation, energy conservation, and efficiency [1,4–6,15,35,36]. This organization is useful because it identifies the main ideas that students should encounter. However, a list of topics does not by itself specify how these ideas should be connected during reasoning. Students can learn the terms “kinetic energy,” “potential energy,” “energy transformation,” and “energy conservation” without understanding how to use those terms to analyze a physical process. From a knowledge integration perspective, the central instructional challenge is to help students organize these ideas into a coherent explanatory structure [22,23].

The first step in constructing such a framework is to identify a central relation that can coordinate the target ideas. For the present ninth-grade energy unit, we selected the work and energy relation as the central organizing relation. This choice is supported by several strands of PER. Warren argued that work has a central role in making energy intelligible [41]. Jewett emphasized that work and systems are both essential for reducing students' confusion about energy [8,9]. Lawson and McDermott showed that students have difficulty applying work and energy ideas even in mechanics contexts that seem familiar to instructors [10]. Lindsey, Heron, and Shaffer further showed that students' difficulties are closely connected to system choice and to reasoning about extended systems [11,12]. Van Heuvelen and Zou showed that multiple representations of work and energy processes can help students connect equations with physical processes [42]. Together, these studies suggest that work can help students connect forces, interactions, system boundaries, and energy changes.

At the same time, the framework must avoid an over-generalized claim. Work is not treated here as the only process by which energy is transferred or transformed. Heating, radiation, electrical transfer, and other mechanisms are important in broader energy instruction [3,13,14,31,35–40]. Instead, the work and energy relation is used as a central organizing relation for the target unit because the unit includes many mechanics-rich contexts

and because the curriculum explicitly connects doing work with energy transfer and transformation. Within this instructional domain, work provides students with a process-based way to ask why energy changes, rather than only describing that energy changes.

To provide a coherent basis for the instructional design, we developed the energy conceptual framework shown in Fig. 1. The framework integrates the theoretical and empirical considerations outlined above. It organizes the target content around the work-energy relation and represents energy-change processes and energy conservation as interconnected elements of reasoning. Within this framework, energy forms are treated as conceptual resources rather than as isolated learning targets. Energy forms such as kinetic energy, gravitational potential energy, elastic potential energy, chemical energy, internal energy, and thermal energy are useful because they help specify how energy is stored or manifested in a chosen system. However, prior research has shown that students may memorize form labels without using them productively in explanations [3,15,43]. Therefore, the framework embeds energy forms within reasoning about systems, interactions, and changes.

Energy transfer, energy transformation, and energy dissipation can be integrated into the broader category of energy change. Energy transfer refers to the process by which energy crosses a system boundary, typically through work, heating, radiation, or other mechanisms. Energy transformation refers to a change in energy form within a chosen system or across coupled systems. Energy dissipation is interpreted as a pattern of change in which energy spreads into a larger system, often as internal energy, and becomes less available for producing visible macroscopic motion [13,14,16]. This treatment is consistent with the perspective emphasized in physics education research that students need to track energy changes across systems rather than regard dissipated energy as destroyed or lost [13,14,16]. In this study, these energy-change processes are examined along two analytical dimensions consisting of energy forms and energy systems. The system dimension concerns how energy is redistributed across systems or objects, whereas the form dimension concerns the forms in which energy is stored and how those forms change. In a specific process, changes along these two dimensions often occur simultaneously. Thus, the two crossed arrows between “energy systems” and “energy forms” in Fig. 1 indicate that students need to coordinate these two dimensions when analyzing energy-change processes.

Energy conservation is treated as a constraint on coherent energy accounting. In a properly defined closed or isolated system, the total energy remains constant, although the distribution of energy among objects, fields, and forms may change. Students' difficulty with conservation often arises not from failing to remember the

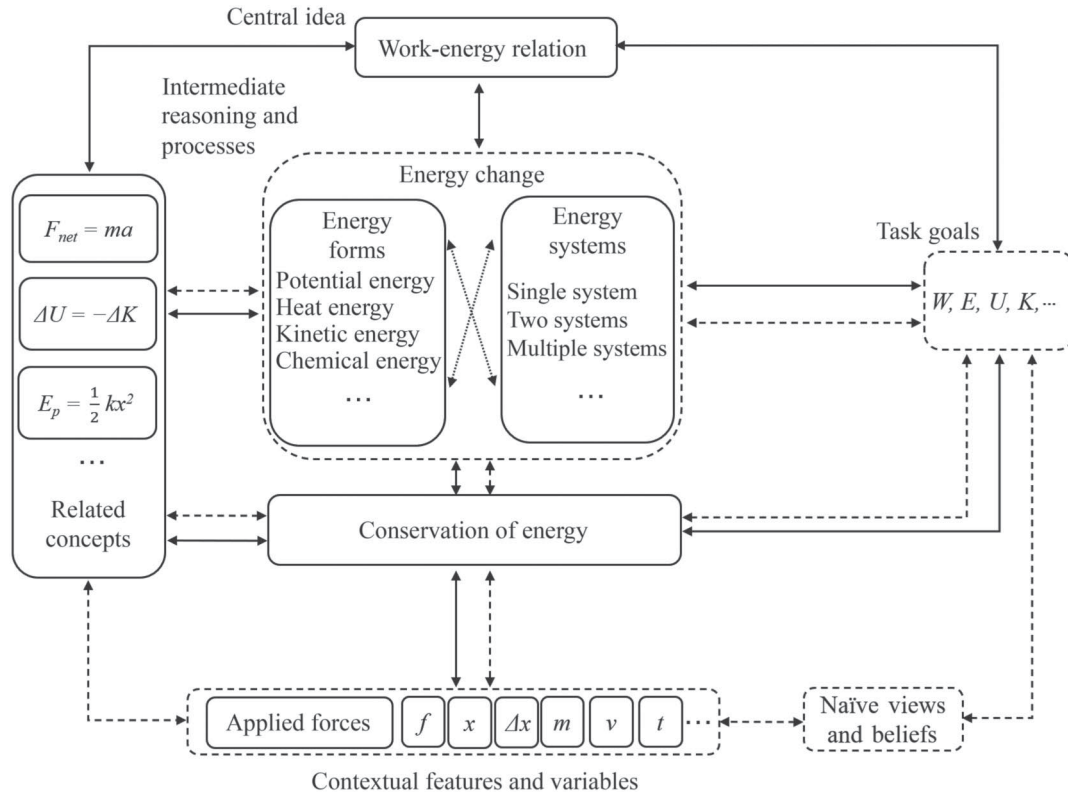


FIG. 1. Energy conceptual framework. The work-energy relation is treated as the central organizing relation for the targeted energy unit. Solid arrows represent more integrated reasoning pathways that connect systems, interactions, energy changes, and conservation. Dotted arrows represent more fragmented or surface-feature-based pathways.

statement that energy is conserved but from not knowing which system to choose and how to account for energy transfers across the system boundary [9,12,13,35–40]. In the present framework, energy conservation is therefore connected to energy-change analysis. Students are expected to define or infer relevant systems, identify interactions, trace energy changes across systems and forms, and then use conservation to evaluate the coherence of the analysis.

The connections among the conceptual elements are represented with two types of arrows as shown in Fig. 1. Solid arrows represent relatively coherent and integrated connections organized around the central relation, whereas dotted arrows represent fragmented connections driven primarily by contextual surface features, local knowledge, or incomplete reasoning. Most pairs of elements are connected by both types of arrows because students with different levels of knowledge integration may establish connections between the same elements in different ways. More specifically, only a dotted arrow is included between “related concepts” and “contextual features and variables” because a direct connection between these elements typically relies more heavily on surface features or experiential associations. Students with relatively coherent knowledge structures, by contrast, tend to organize the connection between these elements through the central

ideas of energy. In contrast, only solid arrows are used to connect the “work-energy relation” with related concepts, “energy change,” and “task goals.” This is because establishing connections between the work-energy relation and these elements requires a developed integrated knowledge structure.

From an instructional perspective, this framework implies that students should not only be asked to identify energy forms or state whether energy is transferred or transformed. They should also be guided to ask what system is being considered, what interactions occur, what work or other energy transfer processes are involved, how energy changes within and across systems, and how the total accounting is constrained by conservation. The framework therefore provides a design basis for an intervention that reorganizes the same curriculum content around a central explanatory relation.

III. STUDY DESIGN AND METHODS

A. Research context and participants

The study was conducted at an ordinary public junior secondary school in an urban area of a prefecture-level city in Central China. According to school-level academic records from previous years, students’ overall academic performance was generally comparable to the local

average. The initial sample consisted of 105 ninth-grade students from two parallel intact classes. Three students had incomplete pretest or post-test data: two students were missing pretest data, one from the intervention group and one from the control group, and one student from the control group was missing post-test data. Because the primary analyses required matched pretest and post-test scores, these three students were excluded using complete-case analysis, and no imputation was performed. The final analytical sample therefore consisted of 102 students, including 52 students in the control group and 50 students in the intervention group. The students were primarily 14–15 years old, and the final sample included 55 boys and 47 girls. Because the participants were Chinese students, all classroom instruction, instructional materials, and assessment administration were conducted in Chinese.

The school implemented instruction according to the national curriculum standards. Before the study, students had learned topics such as work and mechanical energy in the Grade 8 physics curriculum and had some preliminary qualitative experience with these ideas. However, they had not yet received systematic instruction on energy transfer, energy transformation, energy conservation, directionality, or efficiency in the Grade 9 energy unit. The study was conducted immediately before students formally began this part of the curriculum.

In terms of school stage, Grade 9 is the final year of junior secondary education in China and is broadly comparable to the final year of middle school in the United States, although grade configurations and the sequencing of curricular content differ across educational systems. The major topics addressed in the present unit, including energy forms, energy transfer, energy transformation, and energy conservation, substantially overlap with curricular expectations for energy learning at the U.S. middle school level [1,44]. However, neither the Chinese curriculum examined in this study nor the U.S. middle school curriculum framework explicitly foregrounds the work-energy relation as the central relation for organizing the broader system of energy concepts. Thus, although the instructional intervention was developed within the Chinese curriculum context, organizing energy instruction around the work-energy relation may also offer a valuable instructional approach for teaching energy at the U.S. middle school level and in other educational systems with similar curricular expectations.

Because the intervention was implemented within the school's existing class structure, individual random assignment was not possible. The study therefore used a class-level quasi-experimental design. The two classes were selected purposively to support baseline comparability. According to routine school records and the teacher's observations, the two classes had shown broadly similar prior physics achievement, were both regular parallel classes, and were at the middle level within the grade.

Both classes were taught by the same physics teacher, who held a master's degree in physics education and had 6 years of experience teaching junior secondary physics. This arrangement helped hold constant the teacher, teaching schedule, and general school context. Pretest results reported below showed no statistically significant differences between the two groups on the overall score or on any conceptual category score.

B. Instructional content and design rationale

The instructional content was designed according to the Compulsory Education Physics Curriculum Standards, 2022 Edition, issued by the Ministry of Education of the People's Republic of China [44]. The terminology used in the lessons, including “energy transfer,” “energy transformation,” and “work,” followed the standardized expressions used in Chinese secondary physics curricula and textbooks. The unit addressed two main curriculum topics. The first topic was energy and energy transfer and transformation. Students were expected to understand energy and its different forms, describe connections between energy forms and everyday life, recognize through examples that energy can be transferred from one object to another and that different forms of energy can be transformed into one another, and understand that doing work is associated with energy transfer or energy change. The second topic was energy conservation. Students were expected to know the law of conservation of energy, use examples to explain energy conservation in everyday life, analyze problems from the perspective of energy transformation and conservation, understand efficiency, and recognize the directionality of energy transfer and transformation.

Both instructional conditions addressed the same curriculum content, used the same total instructional time, and included the same major example situations and practice tasks. The central difference was how the content was organized. The control group followed the regular textbook sequence used in the local curriculum [45]. This instruction was organized mainly around energy transfer and transformation. The intervention group studied the same content, but the sequence, prompts, and summaries were reorganized according to the conceptual framework. This instruction was organized around the work and energy relation as the central relation connecting systems, interactions, energy changes, and conservation.

C. Control condition: Regular textbook-sequence instruction

The control condition was designed to represent regular textbook-sequence instruction rather than a weakened comparison condition. At the beginning of the unit, the teacher reviewed energy forms that students had previously learned and revisited the definition of work. The lessons then proceeded to energy transfer and transformation, which served as the main organizing content. Students were guided

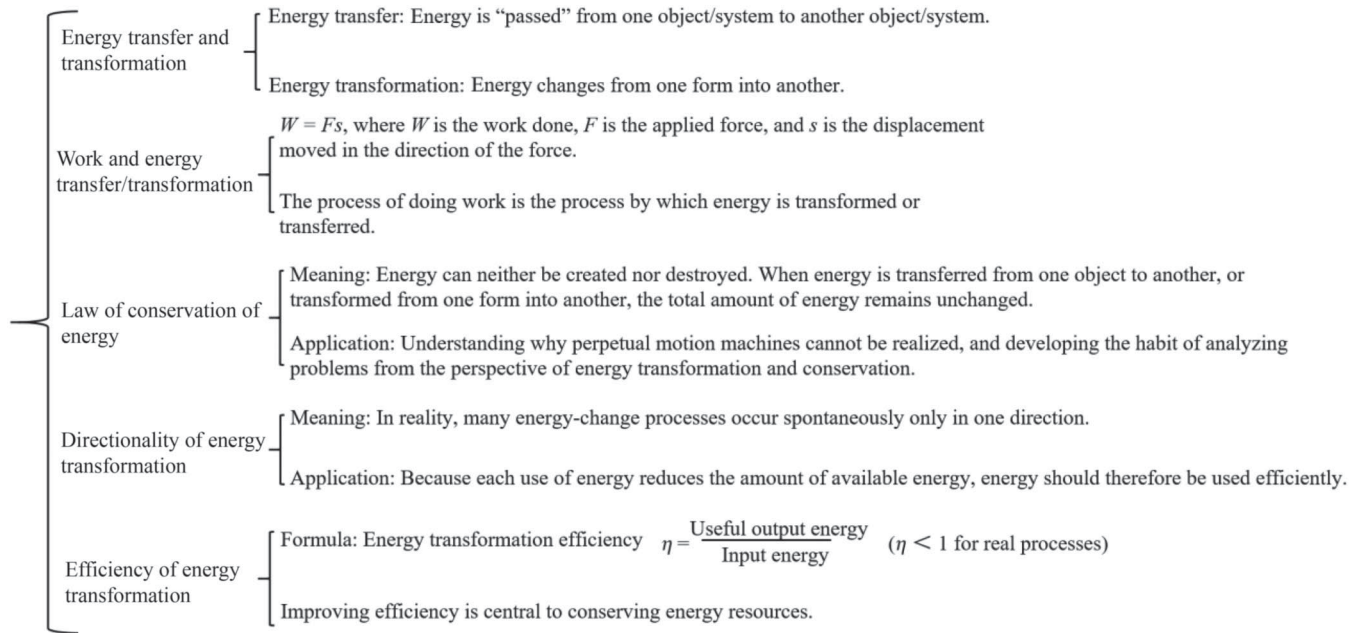


FIG. 2. Energy concept map used in the regular textbook-sequence condition. The map represents the textbook-based organization and instructional sequence of the unit, in which energy transfer and energy transformation served as the main organizing content. It is not intended to be used as a comprehensive model of energy knowledge.

to identify the energy forms involved in common phenomena and to decide whether a process should be described as energy transfer, energy transformation, or both. For example, in the textbook case of a stone rolling down from a height, students were asked which forms of energy were involved and how gravitational potential energy and kinetic energy changed.

In later lessons, the teacher reintroduced work in relation to energy transfer and transformation. In this condition, work appeared as related content, but it was not used as the central mechanism for organizing the analysis of energy change. The teacher then introduced the law of conservation of energy and used it to analyze common phenomena and typical problems. Directionality and efficiency were introduced through their definitions, examples, and calculations.

At the end of the unit, students reviewed the concepts covered in the unit by constructing a concept map consistent with the textbook organization. The teacher then used textbook-style practice tasks to consolidate the main ideas. The review emphasized energy forms, transfer, transformation, conservation, directionality, and efficiency as the main content elements. The concept map used in this condition is shown in Fig. 2.

D. Intervention condition: Conceptual-framework-based instruction

In the intervention condition, the same curriculum content was reorganized around the conceptual framework. At the beginning of the unit, the teacher reviewed work with attention to its physical meaning in concrete

situations. The purpose was to prepare students to use work as a relation linking interactions and energy changes.

The next lesson focused on energy change. Rather than beginning primarily with the labels “transfer” and “transformation,” the teacher introduced a form-by-system way of organizing energy analysis. Students were guided to identify relevant systems, relevant energy forms, and changes in the distribution of energy across systems and forms. For example, in a situation involving a person pushing a box, students considered the person, the box, and the ground or surroundings as relevant systems and discussed how kinetic energy, chemical energy, and internal energy could change depending on the chosen system boundary.

The following lesson explicitly introduced the work and energy relation as the central relation. Students were guided to connect work with changes in energy for a chosen system. The teacher emphasized that the same physical situation can be analyzed differently depending on the system choice. For example, in a falling object situation, if the object alone is treated as the system, gravity is an external force doing work on the object and changing its kinetic energy. If the object and Earth are treated as a combined system, gravitational potential energy decreases while kinetic energy increases. This kind of analysis was intended to help students avoid mixing system choices and to connect work, energy forms, and conservation coherently.

In the lesson on conservation, students were guided to understand conservation as a constraint on energy accounting across systems and forms. Instead of only applying the statement that energy cannot be created or destroyed, students

TABLE I. Representative practice tasks, teacher prompts, and classroom summaries by instructional condition.

Instructional condition	Representative task	Representative teacher prompt	Representative classroom summary
Regular textbook-sequence instruction	Pendulum task. A small ball is attached to a string, released from a raised position, and eventually comes to rest at the lowest point. Question: How can the energy changes in this process be explained?	Consider what form of energy the ball has in its initial state. During the motion, is energy transformed or transferred?	Gravitational potential energy is transformed into kinetic energy during falling and back into gravitational potential energy during rising; some energy is dissipated
Conceptual-framework-based instruction		Consider which forms of energy and which systems are involved in the motion of the pendulum. Why is energy redistributed within and across these systems?	Gravity does positive work on the ball during falling and negative work on the ball during rising; resistive forces do negative work, transferring part of the mechanical energy to the surroundings
Regular textbook-sequence instruction	Collision task. Ball A moves on a horizontal surface and collides with ball B. Ball A slows down noticeably, and ball B starts moving. Question: How can the energy changes in this process be explained?	Consider what form of energy ball A has before the collision. After the collision, is energy transferred or transformed?	Part of ball A's kinetic energy is transferred to ball B, so ball A's kinetic energy decreases and ball B's kinetic energy increases
Conceptual-framework-based instruction		Consider which forms of energy and which systems are involved in the collision. Why is energy redistributed across these systems?	Ball A does positive work on ball B through the contact force, while ball B does negative work on ball A; thus, ball B gains kinetic energy and ball A slows down

traced how energy changes in one system were related to energy changes in another. For dissipative processes, students were asked to account for energy that becomes less visible, such as energy transferred to the surroundings as internal energy through resistive interactions.

In the lessons on directionality and efficiency, students analyzed real processes by considering how some energy spreads into the surroundings during interactions. For example, a pendulum eventually comes to rest because energy associated with visible motion is transferred to the surroundings through air resistance and other resistive processes. Efficiency was discussed as a measure of the fraction of input energy associated with a desired output, not as evidence that energy is destroyed.

At the end of the unit, students reviewed the unit using the conceptual framework. They then completed the same major practice situations as the control group, but the teacher's prompts and classroom summaries emphasized

systems, interactions, work, energy changes, and conservation. Table I provides representative examples.

E. Key differences between the instructional conditions

The two instructional conditions differed primarily in knowledge organization rather than in content coverage. In the control condition, the unit was organized around energy transfer and transformation as content categories. Students learned to identify forms of energy, describe transfer and transformation, state conservation, and calculate efficiency. In the intervention condition, the same content was reorganized around the work and energy relation. Students were asked to analyze systems, interactions, work, energy redistribution, and conservation as connected parts of one explanatory structure.

The two conditions also differed in classroom prompts. In the control condition, prompts tended to ask what

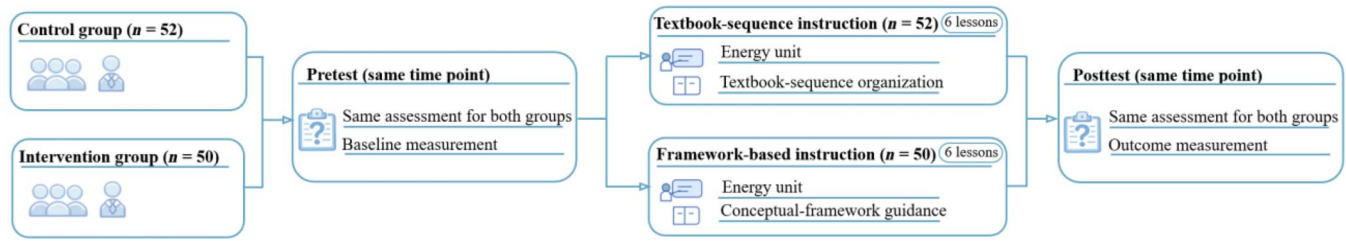


FIG. 3. Procedure of the quasi-experimental study.

energy forms were present and whether energy was transferred or transformed. In the intervention condition, prompts asked which systems were involved, which interactions occurred, whether work or other transfer processes were involved, how energy changed in each system, and whether the resulting account satisfied conservation.

Finally, the two conditions differed in classroom summaries. In the control condition, summaries emphasized the correct classification of energy forms and changes. In the intervention condition, summaries emphasized explanatory pathways connecting interactions to energy changes and conservation.

F. Procedure and implementation

The study used a pretest, intervention, and post-test design. One week before the energy unit began, all participating students completed the energy concept assessment. The control group then received regular textbook-sequence instruction, whereas the intervention group received conceptual-framework-based instruction. Within one week after the unit ended, all students completed the same assessment as a post-test.

Both groups received six class periods of instruction, including five periods of core instruction and one period

TABLE II. Instructional schedule across the six lesson periods.

Lesson period	Control group (regular textbook-sequence instruction)	Intervention group (conceptual-framework-based instruction)
1	Forms of energy and work: Students reviewed the forms of energy they had previously learned and the definition of work in preparation for the subsequent instruction	Work: Students reviewed knowledge related to work, with attention to the physical meaning of doing work in specific situations
2	Energy transfer and transformation: Instructional focus: Students were expected to develop the ability to analyze processes of energy transfer and transformation in different situations	Energy change: Students analyzed energy changes in specific situations by considering both energy systems and energy forms, tracking how energy was redistributed across systems or objects and how its form changed
3	The relation between work and energy transfer/transformation: Students were helped to recognize that processes of energy transformation or transfer are often accompanied by doing work	Work and energy relation (focus of the instruction): Students were expected to develop a deeper understanding of the work and energy relation and to analyze different situations on the basis of this relation
4	Energy conservation: The law of conservation of energy was introduced and then used to analyze relevant phenomena and typical problems	Energy conservation: Conservation was understood from the perspective of the work and energy relation, with emphasis on the connections among energy changes in different systems
5	Directionality and efficiency: Students learned the basic meaning and calculation of the directionality of energy transformation processes and energy conversion efficiency	Directionality and efficiency: Students analyzed the directionality of energy transformation through the work and energy relation and understood why efficiency is less than 1 and where the energy goes
6	Review and practice: Students reviewed the unit content using a concept map and consolidated their learning through practice tasks	Review and practice: Students integrated the unit content using the conceptual framework and consolidated their learning through the same practice tasks

TABLE III. Design features of the energy concept assessment by conceptual category and context type. Energy change and energy conservation items were classified into typical and atypical contexts. Work and energy relation items were classified as atypical context items because this relation is usually less explicitly emphasized in regular instruction as a central idea for organizing energy analysis.

Concept type	Context type	Items
Energy change	Typical	Q5, Q9, Q20, Q23, Q36, Q42
	Atypical	Q2, Q12, Q16, Q25, Q28, Q33, Q40, Q44
Energy conservation	Typical	Q1, Q4, Q7, Q8, Q19, Q22, Q34, Q39
	Atypical	Q10, Q13, Q15, Q17, Q24, Q27, Q29, Q30, Q32, Q37, Q38, Q41, Q43, Q45, Q46
Work and energy relation	Atypical	Q3, Q6, Q11, Q14, Q18, Q21, Q26, Q31, Q35

for review and practice. Because the school scheduled two physics lessons per week, the unit took approximately 3 weeks to complete. Including pretest and post-test administration, the full study lasted approximately 5 weeks.

To support consistency of implementation, the research team prepared lesson plans for both conditions before the intervention. The lesson plans specified instructional objectives, lesson sequence, core examples, practice tasks, and classroom summaries. The teacher was asked to keep instructional time, curriculum content, and the amount of practice comparable across conditions. The two conditions also used the same classroom organization. Instruction was primarily conducted through whole-class teacher explanation and discussion. For the main practice tasks, students first worked individually, then discussed their reasoning in small groups, followed by teacher-led whole-class feedback and summary. Before the unit began, the research team discussed the lesson plans with the teacher to clarify the intended difference between the two conditions. During implementation, the research team checked the instructional sequence against the planned design. The overall procedure is shown in Fig. 3, and the six-period instructional schedule is summarized in Table II.

G. Measurement

Students' learning outcomes were measured with an energy concept assessment developed for the present study. The assessment was a 46-item multiple-choice instrument designed to measure students' understanding and application of energy-related knowledge in the target unit. Items were classified into three conceptual categories: energy change, energy conservation, and the work and energy relation. The assessment included 14 items on energy change, 23 items on energy conservation, and 9 items on the work and energy relation.

The assessment also included typical and atypical contexts. Typical contexts were situations commonly appearing in classroom examples, textbook cases, or homework problems. Atypical contexts were less familiar situations in which students were less likely to succeed by relying only on memorized examples, surface cues, or routine procedures. The purpose of this distinction was to

examine whether students could apply energy knowledge across contexts with different degrees of familiarity.

Most items were adapted or revised from existing instruments and instructional resources, including Ding's Energy Concept Assessment [46], the Energy and Momentum Concept Survey [47], assessment tasks used in energy learning progression research [4–6,35,36], and selected Chinese secondary school textbook and examination items. Because the participants, curriculum, and research purposes differed from those of the original sources, items were reselected, revised, and classified to fit the present study.

The assessment was administered in Chinese. Items originally developed in English were translated and adapted into Chinese. The Chinese-language assessment was reviewed by experts in physics education and secondary physics teaching. Student preinterviews and a small-scale pilot study were also conducted to identify potential linguistic ambiguity. Revisions were made based on expert feedback and student responses.

Before the intervention, the assessment was field tested with an independent sample of 441 students. The field test examined item functioning, score distribution, item difficulty, item discrimination, internal consistency, and item classification. The full 46-item assessment showed good internal consistency, with Cronbach's $\alpha = 0.873$. Details concerning item sources, item revisions, classification criteria, field test results, and additional validity evidence are provided in Supplemental Material [48]. The design features of the assessment by conceptual category and context type are summarized in Table III.

For context-based analyses, typical context and atypical context scores were computed only from the energy change and energy conservation items. The work and energy relation items were analyzed separately and were not included in either context-specific outcome score. This decision followed from RQ2, which examined whether students' performance on the work and energy relation was statistically associated with performance on energy change and conservation items across different context types.

The assessment was used as a measure of performance on the targeted energy ideas and contexts covered by the

unit. The findings should therefore be interpreted as evidence about students' performance on this assessment, rather than as a comprehensive measure of all possible energy learning outcomes.

H. Data analysis

All scores were converted to percentage scores. To examine baseline comparability, Welch's independent-samples t tests compared the control and intervention groups on the pretest total score and the three conceptual category scores. To address RQ1, one-way analyses of covariance were conducted separately for the total score and for the three conceptual categories. In each analysis, instructional group was the independent variable, post-test score was the dependent variable, and the corresponding pretest score was the covariate. The homogeneity of regression slopes assumption was tested before each ANCOVA.

Paired-samples t tests were also conducted within each group to describe pretest to post-test changes. These analyses were descriptive and were not used as the main basis for testing between-group instructional effects. To visualize distributional change, students' overall percentage scores were also divided into three broad descriptive ranges: 0–40, 40–70, and 70–100. These ranges were labeled novice, intermediate, and expert for visualization only. They were not intended as independent diagnostic categories.

To address RQ2, statistical mediation models were estimated with the instructional group as the predictor, post-test performance on the work and energy relation as the mediator, and context-specific post-test scores as the outcomes. Separate models were estimated for typical context and atypical context performance. Bootstrapped confidence intervals were used to evaluate indirect effects. Because the mediator and outcome were measured at the same post-test occasion and because the study used intact classes rather than individual random assignment, these analyses were interpreted as statistical indirect association models, not as evidence of a strict causal mediation mechanism.

All statistical analyses were conducted in R 4.5.1. Welch's independent-samples t tests, paired-samples t tests, and ANCOVA models were conducted using R's stats package. Adjusted means and confidence intervals were estimated using the emmeans package. Effect sizes, including Cohen's d , paired-samples d_z , and partial η^2 , were computed using the effectsize package. Bootstrap percentile confidence intervals for the mediation analyses and the cross-context difference in indirect effects were obtained using the boot package with 5000 resamples.

IV. RESULTS

A. Pretest comparability

Welch's independent-samples t tests were used to examine whether the two groups differed before instruction. As shown in Table IV, no statistically significant differences were found between the control group and the intervention group on the pretest total score or on the three conceptual category scores. All p values were greater than 0.05, and all effect sizes were small, with absolute values of Cohen's d not exceeding 0.26. These results provide evidence that the two groups were broadly comparable on measured energy knowledge before the intervention.

B. Effects of conceptual-framework-based instruction

Figure 4 shows the pretest and post-test mean scores for both groups. The two groups performed similarly on the pretest. After instruction, both groups improved, but the intervention group showed larger gains on the overall assessment and on all three conceptual categories. For the total score, the control group increased from 43.31 to 51.46, whereas the intervention group increased from 45.70 to 66.70. The same pattern appeared for energy change, energy conservation, and the work and energy relation. The difference was especially visible for energy conservation, where the intervention group's mean increased by 24.78 percentage points.

ANCOVAs were conducted to test whether the intervention group outperformed the control group after controlling for pretest performance. The homogeneity of regression slopes assumption was satisfied for all

TABLE IV. Baseline comparison of pretest percentage scores between the control and intervention groups. Welch's independent-samples t tests were used. SE indicates standard error.

Outcome	Control pretest score (SE)	Intervention pretest score (SE)	Mean difference (intervention—control)	t	df	p	d
Overall	43.31 (1.65)	45.70 (2.30)	2.38	0.84	89.61	0.402	0.17
Energy change	54.40 (2.18)	58.86 (2.67)	4.46	1.30	95.38	0.198	0.26
Energy conservation	43.48 (2.42)	46.00 (3.11)	2.52	0.64	93.40	0.524	0.13
Work and energy relation	25.64 (2.10)	24.44 (2.01)	−1.20	−0.41	99.94	0.682	−0.08

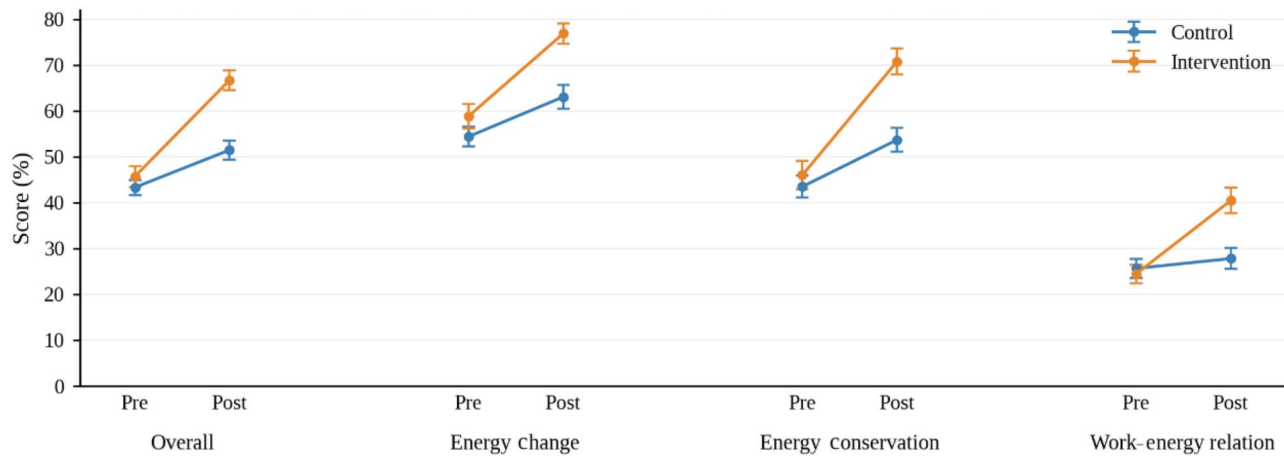


FIG. 4. Pretest and post-test mean percentage scores for the control and intervention groups across the overall test and the three conceptual categories. Error bars represent ± 1 standard error.

outcomes. The interaction between instructional group and pretest score was not significant for the total score, $F(1, 98) = 0.24$, $p = 0.626$; energy change, $F(1, 98) = 0.40$, $p = 0.527$; energy conservation, $F(1, 98) = 0.41$, $p = 0.525$; or the work and energy relation, $F(1, 98) = 0.73$, $p = 0.395$.

As shown in Table V, after controlling for pretest performance, the intervention group scored significantly higher than the control group on the post-test total score, $F(1, 99) = 31.04$, $p < 0.001$, $\eta p^2 = 0.239$. Significant group effects were also found for energy change, $F(1, 99) = 14.16$, $p < 0.001$, $\eta p^2 = 0.125$; energy conservation, $F(1, 99) = 27.38$, $p < 0.001$, $\eta p^2 = 0.217$; and the work and energy relation, $F(1, 99) = 13.40$, $p < 0.001$, $\eta p^2 = 0.119$. The adjusted post-test means indicate that the intervention group outperformed the control group on all four outcomes.

Within-group pretest to post-test changes are shown in Table VI. The control group showed significant gains on the overall score, energy change, and energy conservation. However, the control group's change on the work and energy relation was not statistically significant. The

intervention group showed significant gains on all four outcomes. These within-group results are consistent with the ANCOVA findings, although the ANCOVA results remain the primary evidence for between-group instructional effects.

The distributional transition analysis further illustrates the difference between the two conditions. Figure 5 shows transitions across the three broad score ranges. In the control group, most improvement occurred from the novice range to the intermediate range, and relatively few students moved into the expert range. Among students who began in the novice range, 0.39 moved to the intermediate range, and 0.04 moved to the expert range. Among students who began in the intermediate range, 0.18 moved down to the novice range, and 0.07 moved to the expert range.

In the intervention group, upward movement was more pronounced. Among students who began in the novice range, 0.80 moved to the intermediate range, and 0.05 moved to the expert range. Among students who began in the intermediate range, only 0.04 moved down to the novice range, whereas 0.42 moved to the expert range.

TABLE V. ANCOVA results for post-test percentage scores, with corresponding pretest scores as covariates. Adjusted means are estimated marginal means. B represents the adjusted post-test difference between the intervention and control groups. CI indicates confidence interval.

Outcome	Adjusted post-test mean, control	Adjusted post-test mean, intervention	Group effect, B	95% CI for B	$F(1, 99)$	p	ηp^2
Overall	52.19	65.94	13.75	[8.86, 18.65]	31.04	<0.001	0.239
Energy change	63.49	76.40	12.92	[6.10, 19.73]	14.16	<0.001	0.125
Energy conservation	54.46	69.97	15.51	[9.63, 21.39]	27.38	<0.001	0.217
Work and energy relation	27.64	40.59	12.95	[5.93, 19.96]	13.40	<0.001	0.119

TABLE VI. Within-group pretest to post-test changes in percentage scores. ΔS indicates the mean post-test score minus the mean pretest score. d_z indicates standardized mean change for paired-samples comparisons. For paired-samples t tests, $df = 51$ for the control group and $df = 49$ for the intervention group.

Group	Outcome	Pretest score (SE)	Post-test score (SE)	ΔS	t	p	d_z
Control	Overall	43.31 (1.65)	51.46 (2.09)	8.15	4.42	<0.001	0.61
Control	Energy change	54.40 (2.18)	63.05 (2.60)	8.65	2.90	0.005	0.40
Control	Energy conservation	43.48 (2.42)	53.68 (2.61)	10.20	4.78	<0.001	0.66
Control	Work and energy relation	25.64 (2.10)	27.78 (2.29)	2.14	0.73	0.466	0.10
Intervention	Overall	45.70 (2.30)	66.70 (2.16)	21.00	10.87	<0.001	1.54
Intervention	Energy change	58.86 (2.67)	76.86 (2.26)	18.00	5.66	<0.001	0.80
Intervention	Energy conservation	46.00 (3.11)	70.78 (2.84)	24.78	9.91	<0.001	1.40
Intervention	Work and energy relation	24.44 (2.01)	40.44 (2.76)	16.00	5.37	<0.001	0.76

These descriptive transitions suggest that conceptual-framework-based instruction was associated not only with higher mean scores but also with a more favorable shift in the overall score distribution.

C. Association between the instructional advantage and the work and energy relation

RQ2 asked whether the intervention group's post-test advantage was statistically associated with students' performance on the work and energy relation and whether this association was more pronounced for atypical context performance than for typical context performance. To address this question, statistical mediation models were estimated separately for typical and atypical context outcomes. The context-specific outcomes included only energy change and energy conservation items. Work and energy relation items were treated as a separate mediator.

The results are shown in Table VII and represented schematically in Fig. 6. In both models, path a was statistically significant, with the intervention group performing better on the work and energy relation. Path b was also statistically significant for both typical context and atypical context performance, indicating that stronger performance on the work and energy relation was

associated with better performance in both context types after controlling for instructional group. These findings indicate that the intervention group's post-test advantage was statistically associated with students' stronger performance on the central relation emphasized in the intervention.

For typical context performance, the total effect of the instructional group was significant, $c = 16.330$, $p < 0.001$. The work and energy relation significantly predicted typical context performance, $b = 0.313$, $p < 0.001$. After including the work and energy relation in the model, the direct effect of the instructional group remained significant, $c' = 10.031$, $p < 0.001$. The indirect effect was 6.263, with a 95% percentile bootstrap confidence interval of [3.150, 10.070], accounting for approximately 38.36% of the total effect.

For atypical context performance, the total effect of the instructional group was also significant, $c = 12.639$, $p < 0.001$. The work and energy relation significantly predicted atypical context performance, $b = 0.511$, $p < 0.001$. After including the work and energy relation in the model, the direct effect of the instructional group was reduced and was no longer statistically significant, $c' = 2.332$, $p > 0.05$. The indirect effect was 10.268,

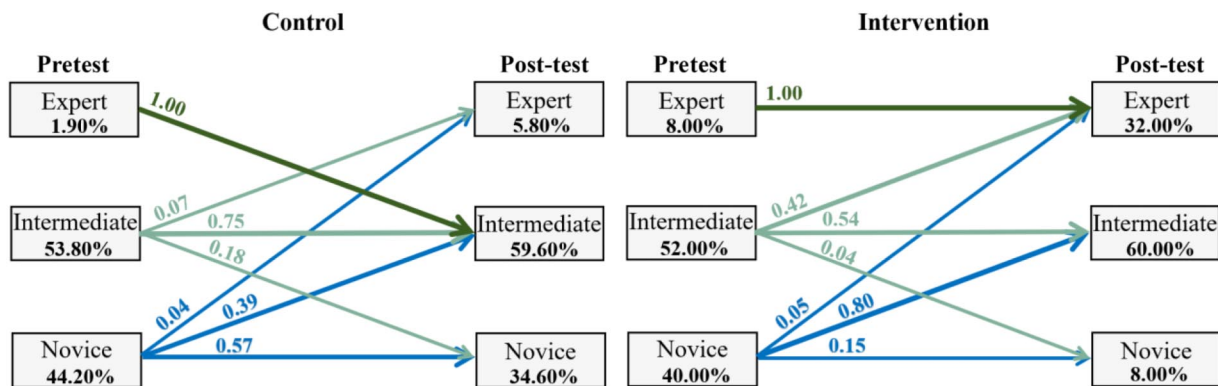


FIG. 5. Transitions across broad overall performance ranges from pretest to post-test by instructional group. The labels novice, intermediate, and expert are descriptive score range labels and are not intended as independent diagnostic classifications. Arrow labels indicate the proportion of students in each pretest range who moved to the corresponding post-test range.

TABLE VII. Statistical mediation analysis of the association between instructional group and context-specific performance through the work and energy relation. Coefficients a , b , c , and c' represent the standard mediation paths. The product ab represents the indirect association, and ab/c represents the proportion of the total association accounted for by the indirect association. Values in brackets are 95% percentile bootstrap confidence intervals for the indirect association.

Outcome	a	b	c	c'	ab [95% CI]	ab/c
Typical context	20.15***	0.31***	16.33***	10.03***	6.26 [3.15, 10.07]	38.36%
Atypical context	20.15***	0.51***	12.64***	2.33 (ns)	10.27 [5.75, 15.18]	81.24%

*** $p < 0.001$; ns, not statistically significant.

with a 95% percentile bootstrap confidence interval of [5.746, 15.181], accounting for approximately 81.24% of the total effect.

A formal cross-context comparison was conducted in a joint post-test model to test whether the indirect association through the work and energy relation differed between typical and atypical context performance. The estimated difference between the two indirect associations was 4.01, with a 95% percentile bootstrap confidence interval of [1.29, 7.46], $p = 0.003$, indicating that the indirect association was larger for atypical context performance than for typical context performance.

Because the mediator and outcomes were measured at the same post-test occasion, and because students were not randomly assigned to conditions, this mediation result should be interpreted cautiously. The model is best understood as a post-test statistical indirect association model rather than as evidence of a strict causal mediation mechanism.

Taken together, the mediation analyses indicate that the intervention group's advantage was statistically associated with performance on the work and energy relation. The post-test model suggests that this association was especially strong for atypical context performance, which is consistent with the theoretical expectation that a central

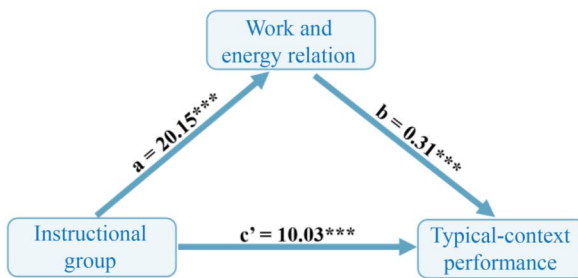
conceptual relation may be particularly useful when familiar surface cues are less available.

V. DISCUSSION

This study examined whether reorganizing a ninth-grade energy unit around the work and energy relation could support students' knowledge integration. The findings provide classroom-based evidence that conceptual-framework-based instruction improved students' performance on energy-related tasks. After controlling for pretest performance, the intervention group outperformed the control group on the overall assessment and on all three conceptual categories: energy change, energy conservation, and the work and energy relation. The intervention group also showed larger within-group gains and a more favorable distributional shift from lower to higher score ranges.

These results are consistent with the knowledge integration perspective. Students' difficulty with energy is often not a lack of exposure to terms such as energy transfer, energy transformation, and conservation. Rather, the difficulty is that these ideas remain weakly connected and strongly tied to familiar situations [3,6,15,22,23].

(a) Typical-Context Performance



(b) Atypical-Context Performance

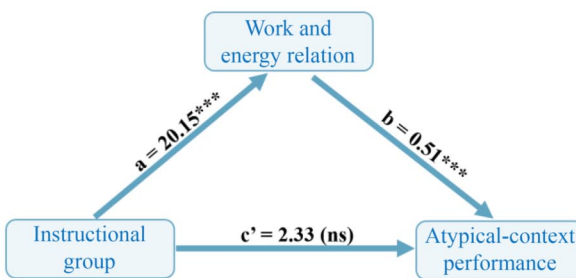


FIG. 6. Statistical mediation models for (a) typical context performance and (b) atypical context performance. Values shown along the paths are unstandardized coefficients rounded to two decimal places. Path a represents the association between instructional group and work and energy relation performance; path b represents the association between work and energy relation performance and the context-specific outcome after controlling for instructional group; and path c' represents the direct association between instructional group and the outcome after including work and energy relation performance in the model. Path a is identical across the two models because the same mediator model and analytic sample were used in both analyses. For both models, the total effects, denoted by c , and the indirect effects, denoted by ab , are reported in Table VII. Asterisks indicate statistical significance and are not part of the path labels. *** $p < 0.001$; ns, not statistically significant.

The intervention addressed this problem by making the relations among systems, interactions, energy changes, and conservation explicit. Students were repeatedly prompted to identify relevant systems, analyze interactions, connect work with changes in energy, and use conservation to check the coherence of the account. This organization appears to have helped students use energy ideas as connected reasoning resources rather than as isolated content labels.

The especially large effect on energy conservation is theoretically meaningful. Prior PER has shown that energy conservation is difficult because students must decide what system is being considered, what crosses the system boundary, and how imperceptible energy changes should be accounted for [9,12–14,35–40]. In regular instruction, conservation can become a declarative principle that students apply only when the problem resembles familiar textbook examples. In the intervention, conservation was connected to a process of tracing energy changes across systems and forms. This may explain why the intervention group showed a strong advantage on conservation items. The finding supports prior arguments that conservation becomes more usable when students are supported in systems-based energy tracking rather than only in recalling the conservation statement [13–16,35–40].

The results also support the productive role of the work and energy relation in the target instructional domain. The intervention group improved substantially on the work and energy relation, whereas the control group did not show a significant gain on this category. This contrast suggests that merely covering work as related content in a textbook sequence may not be sufficient for students to use work as an organizing relation. When work was explicitly connected to systems, interactions, and energy changes, students were more likely to perform well on tasks requiring this relation. This finding extends prior research on students' difficulties with work and energy [10–12] and prior intervention work on work and mechanical energy [32] by showing that a work-centered organization can also support a broader secondary energy unit when it is carefully embedded in systems-based reasoning.

The mediation analysis provides additional evidence about the nature of the intervention advantage. In both typical and atypical contexts, the intervention advantage was statistically associated with students' performance on the work and energy relation. In the post-test model, this indirect association was larger for atypical contexts. This pattern is consistent with the view that central conceptual relations are especially useful when students cannot rely on familiar surface cues. In typical contexts, students may succeed partly by recognizing common examples or routine solution forms. In atypical contexts, success may depend more strongly on whether students can construct a principle-based analysis. This interpretation aligns with research on expert and novice

problem representation, which shows that deep structure becomes more important when surface similarity is reduced [19–21,49–51].

However, the mediation findings should not be over-interpreted. The work and energy relation measure and the context-specific outcome measures were both obtained at post-test, and the study used intact classes rather than individual random assignment. Therefore, the mediation models do not establish a causal mechanism. In addition, all work and energy relation items were treated as a separate central relation category, and these items may share method features with the atypical context tasks. The safest conclusion is that the intervention advantage was statistically associated with students' performance on the central relation emphasized by the intervention and that the stronger atypical context pattern is suggestive but not definitive.

For classroom practice, the study suggests that improving energy instruction may not require adding many new topics or increasing instructional time. Both groups in this study covered the same curriculum content for the same number of class periods. The key difference was how the content was organized and how students were prompted to reason. The intervention suggests a practical instructional sequence: begin by clarifying the meaning of work in concrete interactions, analyze energy changes through systems and forms, use the work and energy relation to connect interactions with energy changes, and treat conservation as a constraint on complete energy accounting. This sequence may help students move beyond naming energy forms toward explaining energy processes.

The study also has implications for the design of energy assessments. If instruction aims to promote integrated understanding, assessments should not focus only on familiar textbook contexts or isolated definitions. The inclusion of typical and atypical contexts made it possible to examine whether students could apply energy reasoning beyond familiar surface features. The separate work and energy relation category also made it possible to test whether performance on the central relation was associated with broader energy performance. Future assessment work could further refine this design by including open response items, interviews, and representational tasks that reveal how students choose systems and construct energy accounts.

The study contributes to PER literature in several ways. It extends conceptual-framework-based instruction to a broader secondary energy unit beyond the narrower topic of work and mechanical energy. It connects the conceptual-framework tradition with PER on systems-based energy reasoning, energy tracking, and dissipation. It also adds evidence from a Chinese secondary school context, which broadens the range of settings in which conceptual-framework-based instruction has been examined. Finally, by analyzing both instructional effects and statistical indirect associations, the study begins to examine not

only whether the intervention worked but also whether the observed advantage was aligned with the theoretical structure of the instructional design.

VI. LIMITATIONS

Several limitations should be considered when interpreting the findings. First, the study used a class-level quasi-experimental design with two intact classes from one school. Instructional condition was therefore fully confounded with class membership. Although the two classes were selected to be comparable, were taught by the same teacher, followed the same schedule, and showed no significant pretest differences, unmeasured class-level factors may have contributed to the observed effects. The results should therefore be interpreted as promising classroom-based evidence rather than as definitive causal evidence.

Second, the analysis was conducted at the student level, but the intervention was assigned at the class level. With only two classes, it was not possible to estimate a multilevel model that separates student-level and class-level variance. Future research should include more classes and teachers so that hierarchical models or cluster randomized designs can be used.

Third, the intervention lasted only six class periods, and the post-test was administered within one week after the unit. The study therefore provides evidence about short-term learning outcomes. It does not show whether the observed gains would persist over time or transfer to later physics topics.

Fourth, the assessment was a multiple-choice instrument focused on the target energy unit. Although the instrument showed good internal consistency in a field test and was designed to align with the conceptual framework, multiple-choice responses do not reveal the full structure of students' reasoning. Interview data, written explanations, and classroom discourse analysis would provide stronger evidence about how students used systems, work, and conservation in their reasoning.

Fifth, the mediation analysis was statistical and exploratory. Because the mediator and outcomes were measured at the same post-test occasion, the mediation results should be interpreted as evidence of association rather than as evidence of a causal pathway. Future studies should measure the proposed mediator and outcomes at separate time points and examine whether changes in the work and energy relation predict later changes in energy performance.

VII. CONCLUSION

This study developed and examined a conceptual-framework-based instructional intervention for a

ninth-grade energy unit. The intervention reorganized the same curriculum content used in regular textbook-sequence instruction around the work and energy relation as a central organizing relation connecting systems, interactions, energy change, and conservation. Compared with the control group, the intervention group showed significantly higher post-test performance on the overall assessment and on the categories of energy change, energy conservation, and the work and energy relation after controlling for pretest performance.

The findings suggest that students' energy learning can be supported by instruction that makes conceptual relations explicit. Rather than treating energy forms, transfer, transformation, and conservation as separate content elements, the intervention helped students connect these ideas through process-based reasoning. The statistical mediation analyses further suggested that the intervention advantage was associated with students' performance on the work and energy relation, especially in atypical contexts in the post-test model. This contextual pattern should be interpreted cautiously, but it is consistent with the theoretical expectation that integrated conceptual structures support reasoning beyond familiar surface cues.

Overall, the study provides evidence that conceptual-framework-based instruction can support knowledge integration in secondary energy learning. It also highlights the value of designing energy instruction around coherent reasoning pathways that connect systems, interactions, energy changes, and conservation. Future research should examine this instructional approach across more classrooms, teachers, and school contexts, include delayed post-tests, and use qualitative data to investigate how students construct and apply integrated energy explanations.

ACKNOWLEDGMENTS

This work is supported in part by the National Education Science Planning Doctoral Project (2025), China, "Research on Large-scale Dynamic Diagnosis and Precise Intervention of Scientific Cognitive Conflict Empowered by Digital Technology" (Grant No. FCA250477). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agencies.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

- [1] National Research Council, *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (The National Academies Press, Washington, DC, 2012).
- [2] L. Bao and K. Koenig, Physics education research for 21st century learning, *Discip. Interdiscip. Sci. Educ. Res.* **1**, 2 (2019).
- [3] J. Nordine, D. Fortus, Y. Lehari, K. Neumann, and J. Krajcik, Modelling energy transfers between systems to support energy knowledge in use, *Stud. Sci. Educ.* **54**, 177 (2018).
- [4] K. Neumann, T. Viering, W. J. Boone, and H. E. Fischer, Towards a learning progression of energy, *J. Res. Sci. Teach.* **50**, 162 (2013).
- [5] C. F. Herrmann Abell and G. E. DeBoer, Investigating a learning progression for energy ideas from upper elementary through high school, *J. Res. Sci. Teach.* **55**, 68 (2018).
- [6] H.-S. Lee and O. L. Liu, Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective, *Sci. Educ.* **94**, 665 (2010).
- [7] M. Kubsch, What affects the continued learning about energy? Evidence from a 4-year longitudinal study, *J. Res. Sci. Teach.* **61**, 975 (2024).
- [8] J. W. Jewett Jr., Energy and the confused student I: Work, *Phys. Teach.* **46**, 38 (2008).
- [9] J. W. Jewett Jr., Energy and the confused student II: Systems, *Phys. Teach.* **46**, 81 (2008).
- [10] R. A. Lawson and L. C. McDermott, Student understanding of the work-energy and impulse-momentum theorems, *Am. J. Phys.* **55**, 811 (1987).
- [11] B. A. Lindsey, P. R. L. Heron, and P. S. Shaffer, Student ability to apply the concepts of work and energy to extended systems, *Am. J. Phys.* **77**, 999 (2009).
- [12] B. A. Lindsey, P. R. L. Heron, and P. S. Shaffer, Student understanding of energy: Difficulties related to systems, *Am. J. Phys.* **80**, 154 (2012).
- [13] A. R. Daane, S. B. McKagan, S. Vokos, and R. E. Scherr, Energy conservation in dissipative processes: Teacher expectations and strategies associated with imperceptible thermal energy, *Phys. Rev. ST Phys. Educ. Res.* **11**, 010109 (2015).
- [14] R. G. Tobin, S. J. Lacy, S. Crissman, N. Haddad, O. Wentink, and L. Seeley, Where does energy go when it is “gone”? Promoting understanding of energy dissipation, *Am. J. Phys.* **87**, 569 (2019).
- [15] J. Nordine, J. Krajcik, and D. Fortus, Transforming energy instruction in middle school to support integrated understanding and future learning, *Sci. Educ.* **95**, 670 (2011).
- [16] A. R. Daane, S. Vokos, and R. E. Scherr, Goals for teacher learning about energy degradation and usefulness, *Phys. Rev. ST Phys. Educ. Res.* **10**, 020111 (2014).
- [17] E. Kim and S.-J. Pak, Students do not overcome conceptual difficulties after solving 1000 traditional problems, *Am. J. Phys.* **70**, 759 (2002).
- [18] M. Alonso, Problem solving vs. conceptual understanding, *Am. J. Phys.* **60**, 777 (1992).
- [19] M. T. H. Chi, P. J. Feltovich, and R. Glaser, Categorization and representation of physics problems by experts and novices, *Cogn. Sci.* **5**, 121 (1981).
- [20] P. T. Hardiman, R. Dufresne, and J. P. Mestre, The relation between problem categorization and problem solving among experts and novices, *Mem. Cognit.* **17**, 627 (1989).
- [21] A. Mason and C. Singh, Assessing expertise in introductory physics using categorization task, *Phys. Rev. ST Phys. Educ. Res.* **7**, 020110 (2011).
- [22] M. C. Linn, The knowledge integration perspective on learning and instruction, in *The Cambridge Handbook of the Learning Sciences*, edited by R. K. Sawyer (Cambridge University Press, Cambridge, 2005), pp. 243–264.
- [23] O. L. Liu, K. Ryoo, M. C. Linn, E. Sato, and V. Svihla, Measuring knowledge integration learning of energy topics: A two-year longitudinal study, *Int. J. Sci. Educ.* **37**, 1044 (2015).
- [24] W. Xu, Q. Liu, K. Koenig, J. Fritchman, J. Han, S. Pan, and L. Bao, Assessment of knowledge integration in student learning of momentum, *Phys. Rev. Phys. Educ. Res.* **16**, 010130 (2020).
- [25] Z. Liu, S. Pan, X. Zhang, and L. Bao, Assessment of knowledge integration in student learning of simple electric circuits, *Phys. Rev. Phys. Educ. Res.* **18**, 020102 (2022).
- [26] D. Tong, J. Liu, Y. Sun, Q. Liu, X. Zhang, S. Pan, and L. Bao, Assessment of student knowledge integration in learning work and mechanical energy, *Phys. Rev. Phys. Educ. Res.* **19**, 010127 (2023).
- [27] L. Bao and J. C. Fritchman, Knowledge integration in student learning of Newton’s third law: Addressing the action-reaction language and the implied causality, *Phys. Rev. Phys. Educ. Res.* **17**, 020116 (2021).
- [28] L. Xie, Q. Liu, H. Lu, Q. Wang, J. Han, X. M. Feng, and L. Bao, Student knowledge integration in learning mechanical wave propagation, *Phys. Rev. Phys. Educ. Res.* **17**, 020122 (2021).
- [29] C. Lu, Y. Liu, S. Xu, S. Zhou, H. Mei, X. Zhang, L. Yang, and L. Bao, Conceptual framework assessment of knowledge integration in student learning of measurement uncertainty, *Phys. Rev. Phys. Educ. Res.* **19**, 020145 (2023).
- [30] D. Ye, J. Qian, W. Xu, Y. Lu, S. Wang, L. Xiao, and L. Bao, Assessment of knowledge integration in student learning of galvanic cell: An interdisciplinary approach connecting physics and chemistry, *Phys. Rev. Phys. Educ. Res.* **20**, 020129 (2024).
- [31] Z. Liu, S. Pan, and L. Bao, Effectiveness of conceptual-framework-based instruction on promoting knowledge integration in learning simple electric circuit, *Phys. Rev. Phys. Educ. Res.* **20**, 020113 (2024).
- [32] D. Tong, H. Wu, H. Ren, Z. Wang, S. Pan, and L. Bao, Promoting knowledge integration in work and mechanical energy through conceptual framework and cooperative learning instruction, *Phys. Rev. Phys. Educ. Res.* **21**, 010163 (2025).
- [33] W. Xu, Y. Jiang, L. Yang, and L. Bao, Conceptual framework based instruction for promoting knowledge integration in learning momentum, *Phys. Rev. Phys. Educ. Res.* **19**, 020124 (2023).
- [34] L. Xie, Y. Li, Q. Fu, Y. Xiao, L. Yang, and L. Bao, Assessing and enhancing university students’ knowledge

- integration in learning electromagnetic induction, *Int. J. Sci. Educ.* **47**, 1659 (2025).
- [35] J.-X. Yao, Y.-Y. Guo, and K. Neumann, Refining a learning progression of energy, *Int. J. Sci. Educ.* **39**, 2361 (2017).
- [36] J.-X. Yao, Y.-X. Liu, and Y.-Y. Guo, Learning progression-based design: Advancing the synergetic development of energy understanding and scientific explanation, *Instr. Sci.* **51**, 397 (2023).
- [37] T. Wyrwich, M. Kubsch, H. Drachsler, and K. Neumann, Tracking students' progression in developing understanding of energy using AI technologies, *Phys. Rev. Phys. Educ. Res.* **21**, 010152 (2025).
- [38] D. Fortus, M. Kubsch, T. Bielik, J. Krajcik, Y. Lehavi, K. Neumann, J. Nordine, S. Opitz, and I. Touitou, Systems, transfer, and fields: Evaluating a new approach to energy instruction, *J. Res. Sci. Teach.* **56**, 1341 (2019).
- [39] M. Kubsch, S. Opitz, J. Nordine, K. Neumann, D. Fortus, and J. Krajcik, Exploring a pathway towards energy conservation through emphasizing the connections between energy, systems, and fields, *Discip. Interdiscip. Sci. Educ. Res.* **3**, 2 (2021).
- [40] K. Fiedler, M. Kubsch, K. Neumann, and J. Nordine, Supporting learning about energy with fields: Evidence from a mixed-methods study, *J. Res. Sci. Teach.* **62**, 1859 (2025).
- [41] J. W. Warren, Energy and its carriers: A critical analysis, *Phys. Educ.* **18**, 209 (1983).
- [42] A. Van Heuvelen and X. Zou, Multiple representations of work-energy processes, *Am. J. Phys.* **69**, 184 (2001).
- [43] G. Swackhamer, Cognitive resources for understanding energy (2005).
- [44] Ministry of Education of the People's Republic of China, *Physics Curriculum Standards for Compulsory Education, 2022 Edition* [in Chinese] (Beijing Normal University Press, Beijing, 2022).
- [45] People's Education Press Curriculum and Teaching Materials Research Institute, *Physics, Grade 9, Complete Volume, Compulsory Education Textbook* [in Chinese] (People's Education Press, Beijing, 2013).
- [46] L. Ding, Designing an Energy Assessment to Evaluate Student Understanding of Energy Topics, Ph.D. thesis, North Carolina State University, Raleigh, NC, 2007.
- [47] C. Singh and D. Rosengrant, Multiple-choice test of energy and momentum concepts, *Am. J. Phys.* **71**, 607 (2003).
- [48] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/wjyg-1hmx> for item sources and modifications, classification criteria, field test results, and additional evidence supporting the interpretation of the assessment scores.
- [49] National Research Council, *How People Learn: Brain, Mind, Experience, and School: Expanded Edition* (The National Academies Press, Washington, DC, 2000).
- [50] M. T. H. Chi and K. A. VanLehn, Seeing deep structure from the interactions of surface features, *Educ. Psychol.* **47**, 177 (2012).
- [51] M. T. H. Chi, J. D. Slotta, and N. De Leeuw, From things to processes: A theory of conceptual change for learning science concepts, *Learn. Instr.* **4**, 27 (1994).