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RESEARCH ARTICLE

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Middle school students' use of the energy concept to engage in new learning: What ideas matter?

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Abstract

One reason for the widespread use of the energy concept across the sciences is that energy analysis can be used to interpret the behavior of systems even if one does not know the particular mechanisms that underlie the observed behavior. By providing an approach to interpreting unfamiliar phenomena, energy provides a lens on phenomena that can set the stage for deeper learning about how and why phenomena occur. However, not all energy ideas are equally productive in setting the stage for new learning. In particular, researchers have debated the value of teaching students to interpret phenomena in terms of energy forms and transformations. In this study, we investigated how two different approaches to middle school energy instruction—one emphasizing energy transformations between forms and one emphasizing energy transfers between systems—prepared students to use their existing energy knowledge to engage in new learning about a novel energy-related phenomenon. To do this, we designed a new assessment instrument to elicit student initial ideas about the phenomenon and to compare how effectively students from each approach learned from authentic learning resources. Our results indicate that students who learned to interpret phenomenon in terms of energy transfers between systems learned more effectively from available learning resources than did students who learned to interpret phenomena in terms of energy forms and transformations. This study informs the design of introductory energy instruction and approaches for assessing how students existing knowledge guides new learning about phenomena.

KEYWORDS

cognitive science, curriculum development, science education

1 | INTRODUCTION

The *Framework for K-12 Science Education* [henceforth Framework] identifies that a primary goal of school science is to prepare students to continue learning about science outside of school (National Research Council [NRC], 2012, p. 1), as students will no doubt encounter unfamiliar scientific and technical contexts in their lives as citizens and workers. To meet this goal, school science should focus on developing students' ability to use a small set of core science concepts that have exceptional explanatory power and broad applicability in science and everyday life (NRC, 2012). Energy is such a concept. The ubiquity of the energy concept makes it exceptionally useful for making sense of both familiar and unfamiliar phenomena. When phenomena are familiar, energy ideas provide a consistent framework for predicting and explaining the behavior of a wide range of systems. When phenomena are unfamiliar, energy serves a useful lens for asking questions and interpreting new information; even if one does not know the mechanisms that underlie a phenomenon, energy ideas are useful for guiding new learning (NL) by providing a lens for efficiently seeking and analyzing new information.

Energy is a powerful idea in science, yet large-scale studies have repeatedly shown that few students develop the understanding of energy that is sufficient to be able to use energy to make sense of phenomena (Herrmann-Abell & DeBoer, 2018; Liu & McKeough, 2005; Neumann et al., 2013; Yao et al., 2017). Many science educators have suggested that students' struggles in learning about energy may actually be attributable to traditional approaches to energy instruction, which may unwittingly hinder students in developing a deep and useful understanding of energy (Bryce & MacMillan, 2009; Chen et al., 2014; Jewett, 2008; Kohn et al., 2018).

One issue at the center of debate about approaches to energy instruction has been the role of energy forms (e.g., chemical energy, gravitational energy, elastic energy) in K-12 energy instruction. Traditionally, curricula present energy as a quantity that exists in different forms then go on to discuss the transformations and transfers of energy that take place as phenomena occur (Hewitt, 2015; Kolodner et al., 2010; Krajcik et al., 2012). We refer to such approaches as "forms-based" (FB) approaches because the idea that energy exists in different forms is foundational to how students are taught to use energy ideas interpret and explain phenomena. FB approaches have been criticized on the grounds that energy forms are not precisely defined (Kaper & Goedhart, 2002; Quinn, 2014), fail to accurately represent the nature of energy (Falk et al., 1983; NRC, 2012), and are not particularly useful for interpreting phenomena—even impeding rather than supporting student understanding (Cooper & Klymkowsky, 2013; Millar, 2014a).

The Framework, in elaborating how the energy concept is used across science disciplines and in everyday life, emphasizes the importance of the idea that energy is transferred between systems for making sense of a wide range of phenomena. In answering the question "What is energy?," the Framework states, "That there is a single quantity called energy is due to the remarkable fact that a system's *total* [emphasis in original] energy is conserved. Regardless of the quantities of energy transferred between subsystems and stored in various ways within the system, the total energy of a system changes only by the amount of energy transferred into and out of the system" (National Research Council, 2012, pp. 120–121). The Framework goes on to say that "The idea that there are different forms of energy, such as thermal energy, mechanical energy, and chemical energy, is misleading" (NRC, 2012, p. 122).

By prioritizing energy transfers between systems rather than energy forms and transformations, the Framework's discussion of the energy concept represents a substantial departure from how energy is traditionally taught. While FB approaches typically include the idea of energy transfer between systems, many science educators have advocated for energy instruction that eliminates the idea of energy forms entirely in favor of presenting energy as a unitary quantity and analyzing phenomena in terms of energy transfers between systems (Brewe, 2011; Ellse, 1988; Falk et al., 1983; Swackhamer, 2005).

Informed by the recommendations in the Framework, the associated performance expectations (PEs) specified within the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), and the literature on energy teaching and learning, we developed an approach to middle school energy instruction—called the systems-transfer (ST) approach—in which students learn to make sense of phenomena by tracking energy transfers between systems (Nordine et al., 2018). In the ST approach to middle school energy instruction, the idea that energy exists in different forms is not needed and therefore not introduced. In previous research, we found that students in the ST approach outperformed students who learned in an FB approach on a range of learning measures (Fortus et al., 2019). Further, we found that ST students developed more parsimonious and well-integrated knowledge networks around the central concept of energy transfer, compared to students who learned in an FB approach (Fortus et al., 2019). Such parsimonious and well-integrated knowledge networks may play a key role in supporting students in using their existing understanding to make sense of new contexts and guide NL (Bransford & Schwartz, 1999; Linn & Eylon, 2000; Schwartz & Goldstone, 2016).

Researchers have highlighted the value of supporting learners in using connecting energy ideas across contexts and disciplinary boundaries (e.g., Becker & Cooper, 2014; Kohn et al., 2018; Lindsey et al., 2019; Nagel & Lindsey, 2015). Yet despite energy's utility as a consistent lens for making sense of a wide range of phenomena and problems, energy instruction has long presented energy in inconsistent ways, even across contexts within a discipline

(Abramovitch & Fortus, 2023; Barak et al., 1997; Lancor, 2014; Osborne et al., 2018). Thus, a central issue in energy instruction is exploring how students might be better supported in developing conceptual understanding and representational models that are useful across a range of contexts, both to make sense of familiar problems and phenomena and to guide NL about novel problems and phenomena.

In this study, we investigated whether instruction that presents energy as a unitary quantity that is transferred between systems prepares middle school students to use their existing energy knowledge to learn about a novel phenomenon, compared to students who learn in a more traditional approach that presents energy as a quantity that exists in different forms and is both transformed and transferred as phenomena occur. To do this, we designed and administered assessments to middle school students who learned about energy in the context of ST and FB energy instruction. These assessments enabled us to: (1) investigate differences in how students from ST and FB approaches learned from informational resources about the novel phenomenon and (2) explore whether differences how ST and FB students engaged in NL may be due to different ways of conceptualizing and using energy to make sense of the phenomenon.

2 | LITERATURE REVIEW

2.1 | What students should know about energy

Energy has long occupied a central position within science education standards (American Association for the Advancement of Science [AAAS], 2009; National Research Council, 2012; NRC, 1996; Sekretariat der Ständigen Konferenz der Kultusminister der Bundesrepublik Deutschland [KMK], 2005); this central position is an acknowledgment that energy is one of the most broadly useful concepts in science. Yet, the energy concept is nuanced and multifaceted, and using it in practice involves activating a set of component ideas, or aspects of energy. Duit (1986, 2014) conducted an analysis of the energy concept in science and identified four basic aspects of the energy concept that he called the "energy quadriga": energy transformation, energy transfer, energy conservation, and energy degradation. To this energy quadriga, some have later identified a fifth aspect that underlies the transformation idea—that energy exists in different forms (see Neumann et al., 2013). These five aspects of energy are commonly taught across science disciplines (Nordine, 2016b), with the most important idea about energy being is its conservation (Feynman et al., 1963). Yet, cross-sectional studies have consistently found that energy conservation is the most difficult aspect of energy for most students to understand and use (Herrmann-Abell & DeBoer, 2018; Lee & Liu, 2010; Liu & McKeough, 2005; Neumann et al., 2013). These studies also reported remarkably similar patterns in terms of how students seem to develop understanding of energy aspects over time, first recognizing that energy has various forms/sources, then that energy can be transferred and/or transformed, and the aspects of energy degradation and conservation are developed last, with few students showing evidence of understanding energy conservation by the end of high school. Accordingly, energy conservation is not an explicit goal for middle school science instruction, where the focus is instead on the various ways that energy is transferred and/or transformed as phenomena occur (e.g., AAAS, 2009; NRC, 2012; Sekretariat der Ständigen Konferenz der Kultusminister der Bundesrepublik Deutschland [KMK], 2005).

The Framework, in laying out a new vision for science learning, stressed that learning about energy alone is not enough. In order for knowledge about energy to be useful, students must engage in "three-dimensional learning" in which they integrate science and engineering practices (SEPs), crosscutting concepts (CCCs), and disciplinary core ideas (DCIs) to make sense of phenomena and solve problems. Energy is somewhat unique in the Framework since it appears prominently as both part of a CCC (energy and matter: flows, cycles, and conservation) and a DCI (in the physical sciences). When describing the role of energy as part of a CCC, the Framework articulates that "Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems′ possibilities and limitations" (National Research Council, 2012, p. 84). As a DCI, the Framework stresses that "Interactions of objects can be explained and predicted using the concept of transfer of energy from one object or system of objects to another" (NRC, 2012, p. 120). Both DCIs and CCCs are a set of conceptual tools that, when used in conjunction with SEPs, help students to use their existing knowledge to make sense of familiar phenomena and to investigate novel phenomena (Duncan et al., 2017; Nordine & Lee, 2021), and the Framework is clear that the tracking energy transfers between systems is central to using energy ideas to make sense of phenomena and solve problems.

In contrast to the heavy emphasis on the tracing transfers of energy between systems in the Framework, middle school energy instruction has long prioritized the idea that energy exists in different forms which are transformed when phenomena occur (see Chen et al., 2014). In the next section, we review different approaches to energy instruction in the literature in terms of how they address and prioritize energy forms/transformations, and transfers.

2.2 | Approaches to energy instruction

Precisely how K-12 energy instruction should present the energy concept has been a matter of considerable debate and pedagogical innovation, with significant discussion focusing on the role of energy forms. One reason for the widespread use of energy forms is that forms language is appealing, as it provides learners with convenient ways to talk about energy (Nordine, 2016a; Quinn, 2014). As such, many researchers have developed innovative approaches that incorporate forms in different ways. On the other hand, others have advocated approaches to energy instruction that eliminate forms altogether in favor of presenting energy as a unitary quantity that cannot be converted between forms—only transferred between systems.

Nordine et al. (2011) describe an FB approach that prioritize energy forms and transformation in order to make sense of phenomena. In this approach, students use a set of indicators (e.g., speed, deformation) to identify the involvement of various forms of energy as phenomena occur, and they learn to interpret phenomena in terms of both transformations between different forms and transfers between objects and systems. Students who learned about energy in this approach improved their conceptual understanding of energy and ability to use energy to make sense of everyday phenomena.

Some researchers have advocated for approaches that prioritize energy transfer processes while backgrounding, but not eliminating, the idea of energy forms. Millar (2014a) criticizes the idea of energy forms but also recognizes the value of forms language for describing the various ways that energy can be stored within systems. Constantinou and Papadouris (2012) developed an epistemologically informed approach that also prioritizes energy transfers while incorporating energy forms. In this approach, learners construct "energy chains" to represent phenomena, which identify the systems that are involved, the forms of energy that are present at various times, and the energy transfer processes between systems. In an empirical study of this approach, the Papadouris and Constantinou (2016) found that middle school students who learned about energy in this way were able to successfully construct energy tracking accounts of phenomena that identified relevant forms and transfers of energy in relation to the systems involved.

Lehavi and Eylon (2018) developed an approach that emphasizes the unitary nature of energy and focuses on the idea of energy change (increases or decreases) as a way to account for processes occurring within and between systems. In this approach, the idea of energy forms is not needed, but Lehavi and Eylon argue that forms language is a simple way for students and teachers to talk about energy. To date, no empirical study of this approach has been published.

Swackhamer (2005) made a theoretical argument that energy instruction should do away with the idea of energy forms entirely and instead present energy as a unitary quantity that can be transferred between physical systems, which include massive objects and the fields that mediate interaction-at-a-distance. The interpretation of fields as real physical systems that can store and transfer energy aligns with field theory (Hobson, 2013; Quinn, 2014), and it is foundational to the origins of the energy concept itself (Coopersmith, 2015). The Framework also recommends that students, beginning in middle school, begin to connect ideas about energy and fields (NRC, 2012, p. 123). Ellse (1988), Falk et al. (1983), and Brewe (2011) have all made theoretical arguments that instruction should eliminate energy forms on the grounds that it is neither physically accurate nor conceptually productive. A transfer-only approach that explicitly connects the idea of energy and fields represents a substantial departure from traditional instruction yet aligns with the vision and recommendations of the Framework.

The literature on the teaching and learning of energy in K-12 includes many theoretical contributions but relatively few empirical studies of instructional interventions. Of the empirical studies, the vast majority of studies focus only on a particular approach without comparing across different instructional approaches. This study is embedded within a broader research and development project in which we: (1) developed the ST approach to teaching energy in middle school, (2) designed an instructional unit based upon this approach, and (3) compared student learning in this new ST unit with an existing energy unit that uses an FB approach.

2.2.1 | The FB unit

The FB unit in this study is part of a comprehensive project-based middle school science curriculum (Krajcik et al., 2012). In the FB unit, students learn to interpret phenomena in terms of transformations between forms of energy, such as gravitational energy, kinetic energy, chemical energy, thermal energy, and so on. Students also learn that energy can be transferred between objects as phenomena unfold, so each phenomenon can be interpreted in terms of energy transformations and/or transfers. Accordingly, the FB unit uses two energy representations, the energy conversion diagram (ECD) and the energy transfer diagram (ETD). Figure 1 shows an ECD for a swinging pendulum, and Figure 2 shows an ETD for colliding carts.

In a randomized controlled trial, the comprehensive curriculum that includes the FB unit has been shown to support NGSS learning outcomes better than a district-adopted textbook (Harris et al., 2015). Study of the particular impact of the FB unit has likewise shown strong learning outcomes specific to the energy concept (Fortus et al., 2015).

2.2.2 | The ST unit

The ST unit was designed as a replacement unit for the FB unit in the comprehensive middle school curriculum of which the FB unit is a part. Accordingly, both units employ project-based

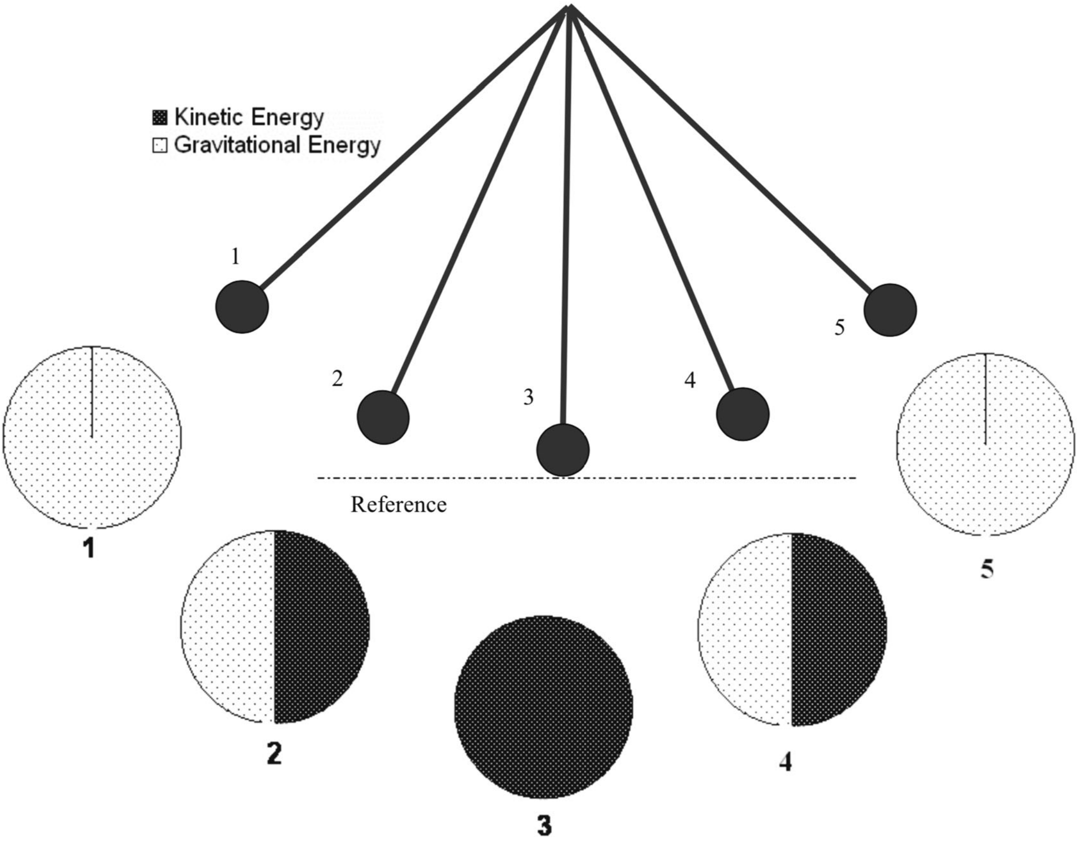

FIGURE 1 Energy conversion diagram (ECD) for a swinging pendulum.

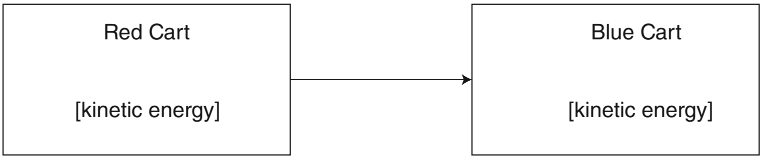

FIGURE 2 Energy transfer diagram (ETD) for a collision between an initially moving red cart and an initially stationary blue cart.

pedagogy (Krajcik & Czerniak, 2018), use the same driving question, require approximately the same instructional time, and address the same NGSS PEs. The ST unit used in this study and its theoretical foundations are described in detail in Nordine et al. (2018).

The most central principle in the ST unit is that energy is a unitary entity that is transferred between interacting systems as phenomena occur. These energy transfers are always accompanied by energy-changing processes within the systems transferring energy. When energy is transferred between interacting systems, the system that energy is transferred *to* undergoes an energy-increasing process while the system that energy is transferred *from* undergoes an energy-decreasing process.

Interpreting phenomena purely in terms of energy transfers requires the recognition of the fields that mediate interaction at a distance (e.g., electric, magnetic) as systems to/from which energy can be transferred. For example, when two magnets are held together and released, each magnet speeds up as energy is transferred to them, and this energy is transferred from the magnetic field that mediates the interaction between the two magnets as its "shape" in space changes (when the configuration of magnets changes). Students can use iron filings to observe these changes in the shape of magnetic fields. A key aspect of the ST approach is that fields are regarded as real physical systems that can transfer energy to/from other systems—such an interpretation of fields and their role in energy transfer aligns with modern physical theory (Coopersmith, 2015; Hobson, 2013; Quinn, 2014) as well as the recommendations for middle school energy instruction in the Framework. It is also important to note that in the ST unit, fields are regarded as a system, even though they are not presented as being composed of constituent parts. More broadly, the ST unit consistently uses the term "system" to refer to the entity to/from which energy is transferred. This corresponds with a more general definition of "system" in which systems identify the part(s) of the universe in which one is interested, and they may be defined according to an object, set of objects, or even a region of space (NRC, 2012). Accordingly, in the ST unit, a system may be a single object/particle (e.g., a billiard ball), a collection of objects/particles (e.g., a molecule), or a field (e.g., magnetic field).

In representing energy transfers between systems, the ST unit incorporates an energy representation called the energy transfer model (ETM), which represents the systems involved in a phenomenon, the direction of energy transfer between these systems, and the associated energy-increasing and energy-decreasing processes. Figure 3 shows an ETM for two colliding carts, and Figure 4 shows an ETM for a swinging pendulum. In both figures, a box represents a system, brackets inside the system box identify the process associated with increasing/decreasing energy, and an arrow shows the direction of energy transfer. In Figure 4, systems

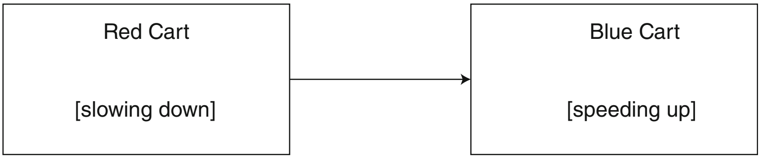

FIGURE 3 Energy transfer model (ETM) for a collision between an initially moving red cart and an initially stationary blue cart.

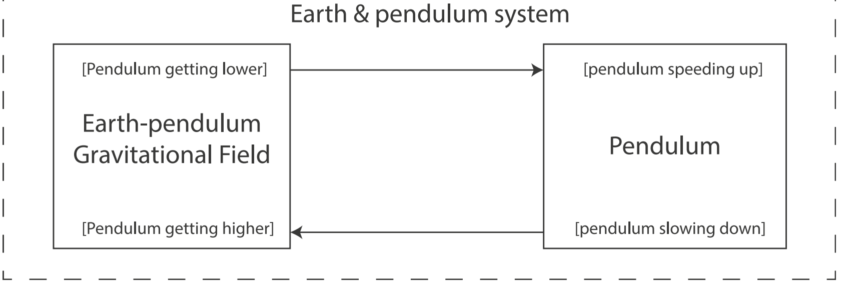

FIGURE 4 Energy transfer model (ETM) for a swinging pendulum.

boxes include both energy-increasing and energy-decreasing processes as energy is transferred between the pendulum and the gravitational field as swinging continues.

Throughout the ST unit, the ETMs grow in complexity as students encounter new phenomena and their explanations of phenomena grow in sophistication (e.g., representing a pendulum that slows down and stops as energy is transferred to the surroundings).

In previous investigations, we have found that the ST unit is comprehensible for middle school students and leads to strong learning gains during instruction (Kubsch et al., 2019, 2021). In a comparison study, we found that students in the ST unit developed knowledge networks that were more strongly organized around the single core idea of energy transfer, while FB students' knowledge networks were less organized and included more core ideas such as forms, transformation, and transfer. We further found that ST students significantly outperformed FB students on assessments of the NGSS PEs addressed by both units (Fortus et al., 2019).

2.2.3 | Summary of approaches to energy instruction

The existing literature on the teaching and learning of energy includes significant debate about the role that the idea of energy forms should play in introductory energy instruction. Much of this debate has consisted of theoretical arguments based upon the nature of the energy concept and more general research into student learning. Empirical study of energy instruction has tended to investigate learning within single approaches and has provided little insight into whether and how different instructional approaches can lead to different outcomes. In previous work, we found that the ST approach led to more parsimonious energy knowledge networks than FB instruction and that the ST approach may better support students in using their energy knowledge to solve assessment tasks that align with the middle school NGSS PEs for energy. In this study, we expand our focus on what it means to use knowledge effectively.

2.3 | Delineating and assessing different types of knowledge use

There has been a growing international emphasis on moving beyond a focus on students *knowing* science ideas and instead stressing students *using* their knowledge in authentic ways in order to solve problems and make sense of phenomena (Finnish National Board of Education (FNBE), 2016; NRC, 2012; OECD, 2019; Sekretariat der Ständigen Konferenz der Kultusminister der Bundesrepublik Deutschland (KMK), 2020). In this study, we focus on two ways that students can use their existing knowledge: (1) *directly applying* (DA) their existing understanding to make sense of sufficiently familiar phenomena/problems and (2) engaging in NL through actively seeking and interpreting available information when phenomena/problems are sufficiently novel.

2.3.1 | Assessing DA of knowledge

Using knowledge through DA occurs when people engage in problem-solving and sensemaking without accessing additional learning resources, either because they are unnecessary (i.e., an expert solving a routine problem) or because they are unavailable (i.e., a student completing a typical school exam). Importantly, directly applying existing knowledge does not necessarily mean rote recall. In the context of school science assessments, students can directly apply their existing knowledge via assessments that measure "three-dimensional science learning" (Harris et al., 2016, 2019; NRC, 2014). Such assessments are designed to diagnose students' proficiency in integrating the three dimensions of science learning identified in the Framework—SEPs, CCCs, and DCIs—in order to make sense of meaningful phenomena and problems that occur within familiar contexts. In a three-dimensional science assessment, students may be asked, for example, to construct a model showing how water can change into hydrogen and oxygen gas, then to use their model to explain how hydrogen and oxygen bubbles are formed when a 9-V battery is placed into water (Harris et al., 2019, p. 62). Three-dimensional science learning assessments are valuable for going beyond simply determining whether students know particular science ideas to focus on how they are able to actively use their knowledge in meaningful contexts (Harris et al., 2016, 2019; NRC, 2014). Three-dimensional science assessments can be used to meaningfully assess students' ability to directly apply their existing knowledge. The critical aspect of assessing DA is that students solve assessment tasks without access to learning resources and must therefore rely only upon their existing knowledge.

2.3.2 | Assessing the use of knowledge to engage in NL

Using knowledge to engage in NL occurs when learners use their existing ideas to guide additional learning when they have access to learning resources. Bransford and Schwartz (1999) referred to learners' readiness to engage in NL as "preparation for future learning" (PFL). The PFL perspective focuses learners' readiness to use their existing domain-specific knowledge to actively guide the process of "reading out" domain-specific information that is critical for NL (diSessa & Wagner, 2005). This active process includes both seeking out new knowledge (e.g., through asking questions) and identifying and assimilating relevant information when it is encountered within a learning resource (e.g., reading a book, watching an educational video). In contrast to the idea of "learning to learn," a learners' preparedness to engage in NL is specific to domains of knowledge, that is, a learner's existing knowledge of pushes and pulls may prepare them to learn more about force concepts but do little to help them learn more about evolution.

In order to assess students' ability to engage in NL in specific domain, assessment instruments must include opportunities to learn new domain-specific ideas. There are several possible approaches to assessing how learners use existing knowledge to guide NL, including following student through formal instruction (e.g., Nordine et al., 2011) and providing students with worked examples embedded within a more traditional assessment (e.g., Schwartz & Martin, 2004). The critical aspect of assessing NL is that learners must have access to relevant learning resources as they solve assessment tasks such that they have opportunities to use their existing knowledge to learn new ideas.

3 | RESEARCH QUESTIONS

Our central hypothesis is that an approach to energy instruction that emphasizes energy transfers between systems and does not rely on the idea that energy is manifested in different forms that can be transformed, better prepares students for learning about novel phenomena. We base this hypothesis on the broader applicability of energy transfer across contexts and phenomena (compared to energy forms/transformation) (NRC, 2012); energy transfer ideas may therefore serve as a more readily useful set of conceptual tools that serve as a lens for interpreting novel phenomena. To test this hypothesis and the rationale behind it, we asked the following research questions:

1. How does performance on an assessment of NL differ between students who participated in the ST unit versus students participated in the FB unit?
2. What ideas do ST unit participants activate when making sense of a novel phenomenon compared to FB unit participants?

4 | METHODS

4.1 | Participants and setting

Study participants were seventh grade students in three middle schools located in the midwestern United States. All schools in the study were enacting the comprehensive project-based middle school science curriculum of which the FB unit is a part, and for which the ST unit is intended to replace the FB unit. The FB and ST units were taught as the second unit in the seventh-grade science sequence. Immediately prior to participating in the ST or FB unit, all students learned about chemical reactions and conservation of matter in a unit that emphasized particle-level interactions. Immediately after the ST or FB unit, all students participated in a unit focusing on atmospheric processes in weather and climate.

Our sample for this study included 85 students from two teachers in different schools who taught the ST unit and 51 students from a third teacher who taught the FB unit in a third school. One ST teacher had 26 years of teaching experience and had taught the ST unit once before; the other ST teacher was new to teaching middle school, but had taught elementary school for 12 years, 8 of which she taught elementary science. The FB teacher had 16 years of teaching experience and had taught the FB unit once before. Throughout the enactment of the ST and FB units, the research team conducted periodic observations and checked in regularly with the teachers to ensure fidelity of implementation.

4.2 | Measures

4.2.1 | Novel phenomenon assessment

To compare how students in the ST and FB units used their existing knowledge to make sense of a novel phenomenon, we developed a novel phenomenon assessment (NPA), which is shown in Appendix S1. We designed the NPA according to four principles:

1. *Phenomena-driven*. Student learning on the task is motivated by a compelling phenomenon, and learning opportunities focus on supporting students in making sense of the phenomenon rather than conveying science content. This mirrors the design of project-based pedagogy and helps to sustain student engagement throughout the extended-time task (Schneider et al., 2020).

2. *Authentic learning resources*. Learning resources were specific to the phenomenon under investigation, rather than general discussions of relevant science ideas (e.g., science textbook passages). In this way, learning resources are a more authentic representation of what students might seek on their own (e.g., during an internet search). Further, learning resources are drawn from what students would be likely to encounter in everyday contexts if they were to seek information about the phenomenon. In addition to enhancing authenticity, this helps to ensure that the learning resources did not unduly advantage students in one instructional approach, for example, through vocabulary or representations specific to the approach.
3. *Assess three-dimensional science learning*. Target assessment tasks require students to integrate science ideas presented in the learning resources with science practices and CCCs. This helps to ensure that learning on the task is not limited to direct recall of information from the learning resources.
4. *Prompts for student reflection*. The NPA provides explicit opportunities for students to activate prior knowledge and reflect on their own learning. These reflections include asking students to consider what they would like to know in order to understand the phenomenon and what they have learned from the learning resource.

These design principles are not only important for the creation of engaging tasks that capture students' interest and provide multiple opportunities to demonstrate competence, they are critical for constructing a task that allows for the fair comparison of how students use their existing knowledge to guide NL across instructional conditions (e.g., ensuring that learning resources are not tailored to one approach) and identifying which prior knowledge students activated as they sought to make sense of the phenomenon at the center of the task.

The NPA administered in this study focused on a reusable instant heat pack, which uses a supersaturated solution of sodium acetate in water. Upon clicking a small metal disc within the heat pack, the solution begins to crystalize in an exothermic process. After activation, the heat pack can be reset by boiling it, which redissolves the crystals and reproduces a supersaturated solution. This phenomenon had not been addressed in either the ST or FB unit yet is accessible using the energy ideas and representational models introduced in both approaches.

The NPA was administered over the course of a single 45-min class period and consists of five phases: (1) problematization, (2) initial ideas, (3) learning resources, (4) reflection, and (5) three-dimensional assessment.

Problematization

In the beginning of the assessment, sample heat packs were given to students, and they mess about, clicking the disc and noticing that the liquid begins to feel more solid and warm as a wave of crystallization spreads through the solution. The teacher then demonstrates that boiling causes the substance inside of the heat pack to return to its liquid form, resetting the heat pack. The teacher then informs students that during class, they will explore how the heat pack works.

Initial ideas

In a subsequent phase, students are asked to record their initial ideas about the heat pack phenomenon. After being reminded that they will learn more about how the heat pack works, they are asked to write down their initial ideas about why a heat pack gets warm as it forms crystals and why boiling resets the heat pack so that it can be used again.

Learning resources

In the learning resources phase of the assessment, students are given a reading about how this type of reusable instant heat pack works and they watch an approximately 5-min video from a popular YouTube science channel (≈1.5 million subscribers) explaining how this type of heat pack works. Both the text and the video explain why the heat pack gets warm after the disk is clicked and why boiling resets it in terms of particle motion, interactions, and rearrangement. By explaining the phenomenon in terms of particle motion, interaction, and rearrangement, the learning resources elaborate the particle-level chemical mechanisms (Macrie-Shuck & Talanquer, 2020; Talanquer, 2018) that underlie the energy changes that occur when a heat pack is activated and reset.

Reflection

In the reflection phase, student prompted to write down what they learned from the learning resources that helps them to better explain how the heat pack is activated and/or reset.

Three-dimensional assessment

Three-dimensional science learning is measured using two items. In the first item, students evaluate claims from three fictitious students regarding why boiling resets the heat pack. They are prompted to identify the best claim and to use what they know about energy to support this claim. In a second item, students are asked to construct a model that explains why the heat pack heats up as crystals form. The items and their scoring rubrics were developed according to the three-dimensional science assessment design procedure outlined by Harris et al. (2019).

To assess three-dimensional learning, it is important that assessments gauge how well students meaningfully integrate across SEPs, DCIs, and CCCs as they solve problems and make sense of phenomena (NRC, 2014). Thus, scoring rubrics were designed to evaluate the extent to which students engaged in an SEP and appropriately used DCI and CCC ideas in order to make sense of the heat pack phenomenon. Accordingly, higher scores corresponded to greater integration across the dimensions. We organized the scoring rubrics according to the elements of a practice; for each element, the rubrics specify how increasing integration with DCI and CCC ideas leads to a higher score. In constructing the rubrics, we took care to use wording and representations that did not favor one instructional approach over the other. The scoring rubric for the NPA is shown in Appendix S1.

To establish item validity and accessibility for participants, we solicited reviews from an expert group of science teachers, scientists, and science educators in order to gather feedback regarding the veracity of information presented and appropriateness of three-dimensional items and scoring rubrics for the target grade level, and we pilot tested the NPA with a small group of students and conducted cognitive pretesting interviews with students at the end of the previous school year. Based on expert feedback, pilot results, and cognitive pretesting interviews, we revised the task and three-dimensional transfer items and scoring rubrics.

4.2.2 | Common energy unit posttest

As a part of the broader project in which this study is embedded, we used the procedure outlined by Harris et al. (2019) to construct three-dimensional assessment items and scoring rubrics aligned to the NGSS PEs that were addressed by both units. In a previous study, we reported that these items demonstrated strong psychometric characteristics, and we detected no meaningful difference in item functioning across the two treatment conditions. Example items and rubrics, along with psychometric characteristics of the Common Energy Unit Posttest items, are given in Fortus et al., 2019.

The Common Energy Unit Posttest consisted of 10 items, which were scored by six experienced middle school teachers who did not teach either the ST or FB unit. Inter-rater reliability for each item was at least 80% with differences resolved through discussion. We constructed student scores using polytomous Rasch modeling (Bond & Fox, 2015).

4.3 | Study design and data collection

To compare how different instructional treatments prepare students for NL, we utilized a study design described by Schwartz and Martin (2004) (see Figure 5).

In this design, students in two different learning treatments complete a target assessment, and a half of the student in each treatment are chosen to have access to learning resources. In our case, the two learning treatments were the ST and FB units and the target assessment were the three-dimensional science assessment items on the NPA. Half of the ST and FB students were randomly chosen to be provided with learning resources about the heat pack phenomenon prior to answering the three-dimensional science assessment items on the NPA. This created four comparison groups: (1) DA for the ST unit, (2) DA for the FB unit, (3) NL for the ST unit, and (4) NL for the FB unit. These four groups allow us to compare how well the ST and FB units prepared students for directly applying their knowledge to make sense of the heat pack phenomenon and how well the ST and FB units prepared students to learn from the text and video resources about the heat pack phenomenon that were provided on the NPA.

4.3.1 | Data collection

We administered the Energy Unit Posttest immediately after the completion of the ST and FB units. This administration was part of the broader project in which this study is embedded.

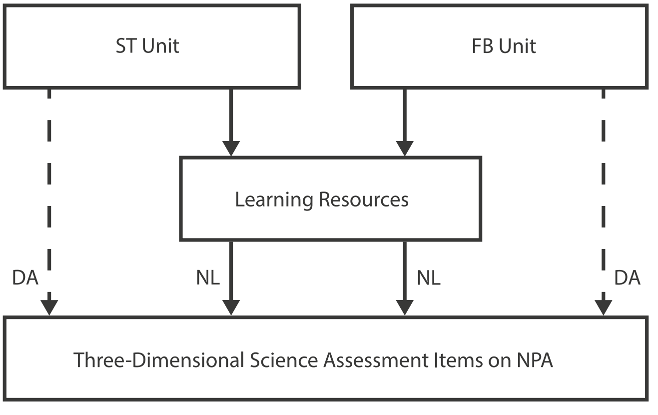

FIGURE 5 Study design for comparing students use of knowledge through direct application (DA) and engaging in new learning (NL) when solving three-dimensional science items on the novel phenomenon assessment (NPA).

We administered the NPA approximately 2 months (during which students were learning about weather and climate in an identical instructional unit) after the conclusion of the ST and FB units. In order to create the four comparison groups (corresponding to each line in Figure 5), we varied order of the NPA phases between students who were randomly assigned to the DA (dashed lines in Figure 5) and NL (solid lines in Figure 5) conditions. The difference in the order of NPA phases is shown in Table 1.

Altering the order of the NPA phases created conditions in which half of the ST participants and half of the FB participants answered the three-dimensional assessment items on the NPA before having access to the learning resources (DA condition), while the other half of ST and FB participants answered the three-dimensional assessment items on the NPA after having access to the learning resources (NL condition).

In order to ensure that students in the DA condition answered the three-dimensional items prior to accessing the learning resources, the NPA was administered in two packets, with the contents of each packet differing between DA and NL conditions. During NPA administration, Packet 1 was collected from students when they were finished, and it was not returned. Table 2 shows the contents of the packets for each condition.

The NPA was administered during the course of a single 45-min class period. Due to the heightened complexity and logistical burden of administering the NPA (e.g., handing out and collecting materials and packets as individual students progress through the NPA), a research assistant was present as teachers administered the NPA in order to ensure that students could finish the full task within the allotted time.

TABLE 1 Order of NPA phases between NL and DA conditions.

	NL condition	DA condition
1	Problematization	
2	Initial ideas	
3	Learning resources	Three-dimensional assessment
4	Reflection	Learning resources
5	Three-dimensional assessment	Reflection

Abbreviations: DA, direct application; NL, NL; NPA, novel phenomenon assessment.

TABLE 2 Contents of NPA packets for NL and DA conditions.

	NL condition	DA condition
Packet 1	Problematization Initial Ideas	Problematization Initial ideas Three-dimensional transfer tasks
Packet 2	Learning resources Reflections on learning Three-dimensional transfer tasks	Learning resources Reflections on learning

Abbreviations: DA, direct application; NL, new learning; NPA, novel phenomenon assessment.

4.4 | Analysis

Student responses on the NPA were scored according to the scoring guide shown in Appendix S1 by two research assistants who we trained to use the scoring guide. Students' responses from each comparison group were mixed together so that the research assistants did not know whether responses were from the ST or FB units or from the NL or DA conditions. We conducted drift checks throughout the scoring process to ensure that scoring remained consistent. Overall, inter-rater reliability was 94%.

4.4.1 | Addressing research question 1

To compare how students from the ST and FB units used their existing knowledge to engage in NL on the NPA, we used students' scores from the Common Energy Unit Posttest and their scores on the three-dimensional assessment items on the NPA.

We used students' scores on the Common Energy Unit Posttest that they achieved immediately after their participation in the ST or FB units. These scores provided information about how well students met the NGSS PEs targeted by both instructional units at the conclusion of instruction. We first used these scores to evaluate the comparability of the four comparison groups on the NPA (see Figure 5). Table 3 shows the size of each group and participants' scores on the Common Energy Unit Posttest. We found no significant difference on this measure between any treatment groups.

To assign scores on the NPA, we summed students' scores across both scoring rubrics for the three-dimensional assessment items on the NPA; each rubric included a maximum score of 6 points, for a total of 12 possible points. We then computed a regression model in which we predicted students' score on the NPA based on their NPA condition (DA or NL), the instructional unit they participated in (ST or FB), and the interaction of NPA condition and instructional unit participation. We included students' scores on the Common Energy Unit Posttest as a covariate. This regression model allows us to estimate the overall effect of access to learning resources across, the overall effect of participating in the ST or FB units, and whether the effect of access to learning resources was different based upon the instructional unit in which students participated.

4.4.2 | Addressing research question 2

To address research question 2, we conducted qualitative content analysis (Mayring, 2014) on the initial ideas about the heat pack phenomenon that students activated during the initial

TABLE 3 Mean standardized scores and standard deviation on the common energy unit posttest for students in each comparison group on the NPA. No differences in scores were significant ($p < 0.05$) between any group.

Instruction unit	Condition	*n*	*M*	*SD*
Systems-transfer	NL	41	0.08	0.47
	DA	44	−0.01	0.83
Forms-based	NL	24	−0.09	0.47
	DA	27	0.00	0.59

ideas phase of the NPA. In this analytical approach, we first read student responses and created initial codes according to the science ideas and/or heat pack features included in those responses. For each code, we identified at least one exemplary student quotation and elaborated a description of each code. Table 4 shows examples of initial codes, elaborations, and exemplary student quotations. After identifying initial codes, we created initial categories to which the initial codes could be assigned. These categories were further reviewed in order to eliminate redundant/overlapping categories. Finally, we identified categories that were relevant to answering research question 2, which focuses on the ideas that students who participated in the ST and FB units activate when initially asked to make sense of the heat pack phenomenon. We used the category system that resulted from our qualitative content analysis to compute the relative frequency of initial ideas activated by students from the ST and FB units.

5 | FINDINGS

5.1 | Research question 1

This research question focuses on whether there was a difference in how the ST and FB units prepared students to learn from the resources provided on the NPA. Figure 6 shows the distribution of NPA scores in the DA and NL conditions, by instructional unit.

TABLE 4 Example initial codes from qualitative content analysis.

Code	Elaboration	Example student quotation
Phase change	Student refers to a matter phase change	"The boiling melts the crystals back to a liquid…"
Thermal energy	Student refers to thermal energy	"…the heat pack gets thermal energy from your hands"
Disk	Student refers to the role of the disk	"…when you push the button it releases energy…"
Particle speed	Student refers to particle speed or motion	"The molecules slow down…"
Particle arrangement	Student refers to particle distance or arrangement	"…the molecules come together…"
Chemical reaction	Student refers to the role of a chemical reaction	"I think there is a chemical reaction."
Energy transfer	Student states that energy transfer is somehow involved or describes an energy transfer process	"…the crystals could transfer energy to the liquid."
Energy transformation	Student states that energy transformation is somehow involved or describes an energy transformation process	"The molecules have chemical energy and form bonds that release thermal energy."
Dissolving	Student refers to the dissolving of crystals during heating	"The boiling water dissolves the hard substance."
Temperature	Student refers to a change in temperature	"The molecules have an increase in temperature"

These results show no difference for either group in the DA condition; student scores were roughly similar on the three-dimensional assessment items when they answered these items without access to learning resources. In the NL condition, students from the ST unit clearly outperformed students from the FB unit. When given access to learning resources about how a heat pack works, ST students scored higher on three-dimensional science assessment items relating to the heat pack phenomenon than their counterparts in the FB unit.

Examining the DA and NL conditions within an instructional unit provides insight into how well students who had access to the learning resources performed on the NPA relative to their peers who participated in the same unit. Students in the ST unit students who had access to learning resources clearly outperformed ST unit students who answered the three-dimensional assessment items without having access to the learning resources, while the benefit of access to learning resources among FB students is less clear.

Our regression analysis confirms the qualitative differences in student scores that are apparent in Figure 6. The regression model predicting students' NPA scores is shown in Table 5.

This analysis reveals two significant predictors: treatment condition (access to learning resources) and interaction effect between treatment and instructional condition. These results indicate that student performance on the NPA was enhanced when they had access to learning resources, but that the effect of the learning resource was moderated by the instructional unit students participated in. Students who learned about energy in the ST unit benefitted more from access to the learning resources than did students who participated in the FB unit. Further, student posttest scores on the Common Energy Unit Posttest were not a significant predictor of student performance across all treatment conditions. This model explains roughly 23% of the variance in student responses.

Overall, our analysis to address research question 1 indicate that students from the ST unit outperformed students from the FB unit in terms of their ability to engage in NL about the instant heat pack phenomenon.

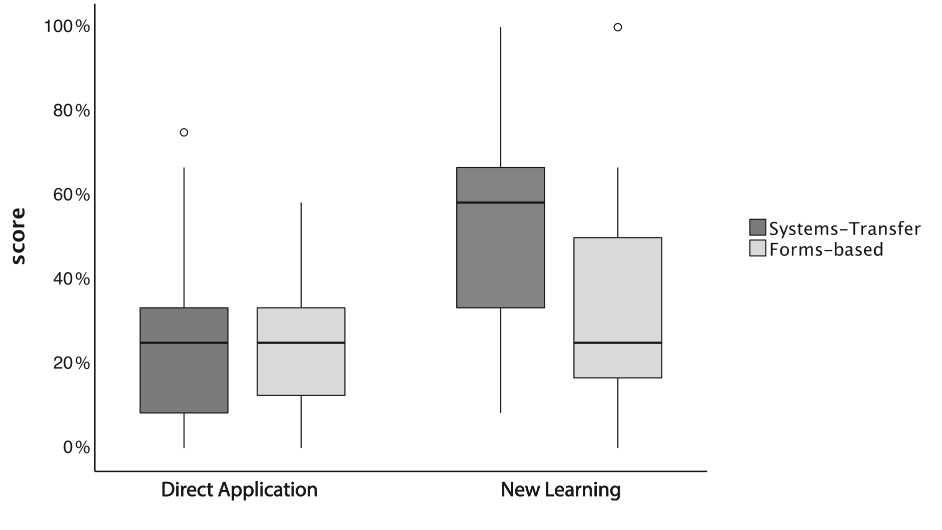

FIGURE 6 Student scores on novel phenomenon assessment (NPA) by participation in the systems-transfer (ST) or FB unit and assignment to direct application (DA) or new learning (NL) condition.

TABLE 5 Regression model predicting student scores on the NPA ($N = 136$).

Variable	*B*	*SE B*	β	*p*
Common energy unit posttest	3.08	3.06	0.08	0.317
Condition (1 = NL condition)	27.6	4.83	0.56	< 0.001
Unit (1 = FB unit)	0.33	5.41	0.01	0.95
Unit × condition	−16.3	7.88	−0.25	0.04
R^2	0.23			

5.2 | Research question 2

In research question 2, we explored whether the differences in student performance may be attributed to the activation of different initial ideas when attempting to make sense of the heat pack phenomenon. Figure 7 shows the ideas activated by students in the initial ideas phase of the NPA. The categories in Figure 7 are those that emerged from our qualitative content analysis, and a student is represented within each category if this idea appeared at least once in their initial responses. Though we did not identify "Energy Transformation" as a final category in our analysis, we included it in Figure 7 because it is the central idea in the FB unit.

The most common idea activated across both instructional conditions was that a chemical reaction was somehow involved. This is not actually the case, but it is aligned with how students had learned about chemical reactions in a previous instructional unit focused on chemical reactions. In this unit, students learned that evidence for chemical reactions includes temperature changes and substances seeming to appear/disappear. Students who were assigned this code invoked the idea of chemical reaction in their initial ideas, for example:

- "There is a chemical reaction to make the crystals so it gets hot." (ST student).
- "Because the clicking metal disk has a chemical reaction with the liquid making it go solid and heat up" (FB student).

Though chemical reaction was the most commonly activated idea to explain the phenomenon across both instructional units, a notably higher percentage of students in the FB group referred to chemical reactions in their initial ideas.

The chemistry unit that preceded the energy unit also included a focus on particle speed and rearrangement during chemical reactions. Students from both instructional units referred to the role of particles in their initial ideas, though this was less than 20% of students in each group. Example responses include:

- "When you boil it, it rearranges the atoms" (ST student).
- "When you click the disk inside the heat pack, the disk releases liquid. The particles in the liquid speed up making the heat pack heat up" (FB student).

Overall, there not notable difference in terms of how, and how frequently, students included the idea of particles, particle speed, or particle rearrangement in their initial ideas.

Differences did appear between instructional conditions in terms of which energy ideas students activated. Students in the ST unit were more likely to activate the idea of energy transfer,

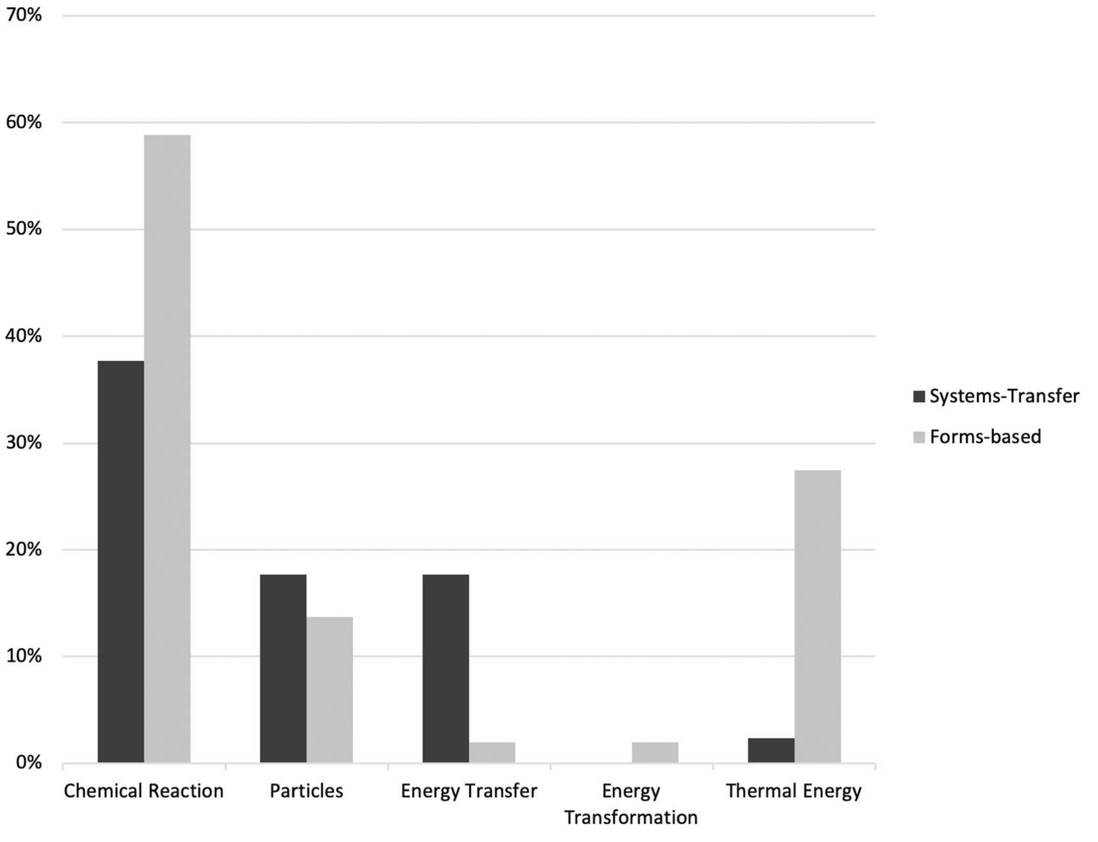

FIGURE 7 Percentage of students in the systems-transfer (ST) and forms-based (FB) units activating ideas with explanatory value on the initial ideas section of the novel phenomenon assessment (NPA).

while students in the FB unit were more likely to activate the idea of thermal energy. Notably, only one student in the FB unit referred to energy transformation. This is important because the core interpretive framework for phenomena in the FB unit is the idea that in every phenomenon, energy is transformed. Conversely, the core interpretive framework in the ST unit is that in every phenomenon, energy is transferred. While approximately one fifth of students in the ST unit explicitly referred to energy transfer in their initial ideas, only one student in the FB unit explicitly referred to transformation.

Overall, our analysis to address research question 2 revealed important similarities and differences in which ideas that students in each instructional condition activated as they attempted to explain the heat pack phenomenon before they had access to learning resources. While both groups activated ideas about chemical reactions, particles, and energy with similar frequency, ST students who activated energy ideas referred almost exclusively to energy transfer, while FB students almost exclusively referred to a specific energy form (thermal energy) without referring to energy transformation.

6 | DISCUSSION

Energy is a central concept in science that is useful for interpreting familiar phenomena and investigating unfamiliar phenomena. In describing how the energy concept is useful in practice, the Framework repeatedly and clearly stresses the importance of tracking energy transfers between systems. Yet, middle school energy instruction traditionally prioritizes the identification of energy forms and transformations above tracking energy transfers between systems. In this study, we compared how transfer-only instruction (the ST unit) and more traditional FB instruction (the FB unit) prepared students to use their existing energy knowledge to make sense of a novel energy-related phenomenon and to engage in NL about the phenomenon when provided with access to learning resources.

In research question 1, we investigated whether students who learned to interpret phenomena in terms of energy transfers between systems (ST unit) were better prepared to use their existing knowledge to engage in NL about a novel phenomenon (instant heat pack) than were students who learned to interpret phenomena in terms of transformations between energy forms (FB unit). We found that while students in the ST and FB unit performed indistinguishably on Common Energy Unit Posttest, ST units more successfully engaged in NL about the instant heat pack phenomenon when they had access to learning resources. In research question 2, we investigated whether differences in students' NL may be attributable to differences in energy ideas that students from different instructional approaches activate as they begin to make sense of the phenomenon. In examining students' initial ideas about how a heat pack works (immediately after they observed the phenomenon), we observed that ST students were more likely to activate energy transfer ideas, while FB students were more likely to activate energy forms ideas (specifically thermal energy)—but not transformation ideas. Taken together, results from both research questions support our hypothesis that learning to interpreting phenomena in terms of energy transfers was more useful for engaging in NL about the instant heat pack than learning to interpret phenomena in terms of energy forms and transformations.

6.1 | Putting our results into context

In our regression analysis (Table 5), we found a significant interaction effect of instructional treatment and access to learning resources while controlling for Common Energy Unit Posttest scores. The size of this interaction effect was 0.25, and its direction indicated that access to learning resources benefitted ST students more than FB students. Using widely used guidance, an effect of this size may be interpreted as moderate (see Cohen, 1988; Fey et al., 2023). Of course, effect sizes alone do not adequately convey the practical significance of the results of an educational intervention (Kraft, 2020). A useful way of exploring the practical significance of the moderate effect we observed is by comparing our results to similar interventions reported within the literature (Lakens, 2013).

We are certainly not the first group to consider the impact that instruction can have on subsequent learning. Since Bransford and Schwartz (1999) proposed the PFL perspective, several groups have attempted to measure the effect of instructional treatments on students' ability to learn during subsequent learning opportunities.

Schwartz and Martin (2004) investigated the influence of "tell-and-practice" versus "invention-based" instruction on ninth grade algebra students' ability to learn from worked example provided to half of the students on a post-instruction assessment. Their study design and results were similar to ours. They reported similar achievement on the post-instruction assessment for all students in tell-and-practice instruction (regardless of access to the worked example) and for students in invention-based instruction who did not have access to the worked example. Only students in invention-based instruction who had access to the learning resource significantly outperformed the other groups. Using ANOVA, they reported a significant three-way interaction effect of instructional method, presence of resource, and pretest to posttest gain. This is similar to our regression results (Table 5), in which we found a moderate interaction effect of instructional treatment and access to learning resources. While Schwartz and Martin did not report effect sizes, the mean score of the highest-performing group was about twice that of the other groups, which is also in line with our results. Overall, their results align with our finding that different instructional approaches can have a significant effect on how well-prepared students are to use their existing knowledge to learn from available resources.

In attempting to replicate the Schwartz and Martin (2004) study in the context of physics, Etkina et al. (2009) compared student learning from a written text based upon their participation in typical laboratory instruction (control), cookbook laboratory instruction (in which students followed a step-by-step method), and innovation laboratory instruction (in which students developed the target concept themselves invented a coefficient to measure it). After instruction, all students received the written text about the target concept, which they were allowed to use to complete a post-instruction assessment. While they did not randomize access to the written text within instructional treatments and therefore did not use the design shown in Figure 5, they did report statistical differences favoring students in the innovation laboratory relative to the other conditions. They concluded that the design of laboratory instruction can influence students' subsequent construction of physics concepts.

In the area of middle school energy instruction, Nordine et al. (2011) followed students who participated in a project-based energy unit that emphasized energy transformations and found that students who learned in this approach were better prepared for learning about energy in their subsequent science course compared to students who had learned about energy in a more piecemeal fashion. Fiedler et al. (2023) studied students who had learned about energy using FB approaches that did or did not include the fields concept. By comparing student learning in a subsequent unit on electricity using ANCOVA, they found that energy instruction that included the fields concept better prepared students for learning about electric energy than did non-fields energy instruction. In their analysis, Fielder, et al., reported a partial $\eta^2 = 0.097$, which may be interpreted as a moderate effect size (Cohen, 1988) and corresponds with the moderate effect that we observed. Both the Nordine, et al., and Fiedler, et al., studies align with our findings that different types of middle school energy instruction can influence how effectively students engage in NL about energy.

Overall, our results align with other studies reporting that instruction influences students' ability to engage in NL. Our study contributes to existing research in two important ways. First, our study deepens our understanding of how different ways of learning to use energy ideas to interpret phenomena may affect students' future use of energy ideas to engage in NL. While existing research has suggested that energy instruction can influence subsequent learning (Fiedler et al., 2023; Nordine et al., 2011), and that transfer-only energy instruction may hold significant advantages over FB energy instruction (Brewe, 2011; Ellse, 1988; Falk et al., 1983; Fortus et al., 2019; Kubsch et al., 2019, 2021; Swackhamer, 2005), this study sheds light on how transfer-only energy instruction may support students in using their energy knowledge to engage in new energy learning. Second, our study informs the design of assessments that can efficiently measure NL. Existing studies have assessed NL by providing access to worked examples or written text as students complete more traditional exams (Etkina et al., 2009; Schwartz & Martin, 2004) or by following students as they participate in subsequent instructional units (Fiedler et al., 2023; Nordine et al., 2011), but we are unaware of other groups who have taken a similar approach to assessing NL in the context learning about a novel phenomenon in a single class period. We believe that the design of the NPA may inform how researchers and practitioners can efficiently go beyond measuring existing student knowledge to gain insight about how students use their current knowledge to engage in NL. In the subsequent sections, we elaborate these two contributions to existing research.

6.2 | Preparing for new energy-related learning: Energy transfer versus transformation

To understand how the ST approach may better prepare students for using their existing energy ideas to learn about novel phenomena, it is helpful to contrast how students learn to use energy ideas within the FB and ST perspectives.

6.2.1 | The FB perspective

Traditional energy instruction relies heavily on the idea that energy exists in different forms (Millar, 2014b). The FB unit is an example of a high-quality implementation of the FB perspective, as it was developed using project-based pedagogy and has been shown to be effective in empirical study (Fortus et al., 2015). In the FB unit, students interpret phenomena by considering what forms of energy seem to be involved based on a set of indicators for different energy forms, for example, speed for kinetic energy and temperature for thermal energy. As they begin to interpret phenomena using an energy lens, they first identify a list of energy forms involved in the phenomenon, then, they determine whether certain energy forms have increased or decreased during the phenomena. Students then describe the phenomena in terms of energy transformation from the form(s) that decreased to the form(s) that increase (Fortus et al., 2013). The role of systems is not foregrounded, nor is the importance of interaction or energy exchange between these systems. For example, if FB students use energy ideas to interpret an exothermic chemical reaction, they might say that chemical reactions convert chemical energy into thermal energy (Fortus et al., 2013, p. 207). While there may be nothing technically wrong with this description, many scholars have criticized the FB perspective on the grounds that diverts students' attention away from the physical changes that occur within systems (Swackhamer, 2005) and that it is not useful for providing insight into how phenomena occur or devices operate (Millar, 2005, 2014a). Simply labeling the energy forms involved in a phenomenon does little to prompt deeper consideration of physical changes or mechanisms involved.

6.2.2 | The ST perspective

When students learn to interpret phenomena in terms of energy transfers between systems, they need to consider three key questions: (1) What systems are interacting? (2) What is the direction of energy transfer between interacting systems? (3) What are the energy increasing/decreasing processes occurring in each system that accompany energy transfers?

The ST perspective focuses on the changes that occur within systems as the phenomena proceeds. To interpret an exothermic chemical reaction from an ST perspective, students recognize that a system of reacting substances transfers energy to the surrounding system (Nordine et al., 2018). This sets the stage for considering underlying mechanisms by explicitly considering the changes in each system. The surroundings undergo an energy increasing process by heating up, and the system of reacting substances undergo an energy decreasing process change as the configuration of particles interacting at a distance (via fields) changes.

6.2.3 | Comparing perspectives

Both the ST and FB perspectives are consistent with the consideration of underlying mechanisms, but they differ in how explicitly they prompt students to attend to them. We noted, for example, that students in both approaches activated the idea of particles, particle speed, and particle rearrangement at comparable rates when initially trying to make sense of the heat pack phenomenon. Further, without access to learning resources, ST and FB students performed similarly on the three-dimensional assessment items about the instant heat pack phenomenon. Yet, when students had access to learning resources, ST unit participants learned more effectively from learning resources that used a particle model to explain activating and resetting an instant heat pack. This difference in NL may be explained by differences in how students conceptualize energy; students in the ST unit activated the idea of energy transfer more frequently, while the most common energy idea activated by FB students was that thermal energy was somehow involved. The ideas of energy transfer and thermal energy are qualitatively different in terms of the subsequent thinking that they prompt. The FB approach can easily lead to analysis that stops after labeling energy forms; on the other hand, by focusing student attention on energy transfers between systems, the ST approach prompts students to consider the physical interactions and processes that accompany energy transfers. Without access to learning resources about the novel instant heat pack phenomenon, neither students from the ST nor FB approaches were able to successfully speculate about the underlying mechanisms that drive the phenomenon. But, by thinking about the phenomenon in terms of energy transfers between systems—rather than identifying energy forms—ST unit participants may have been better prepared to learn about how the instant heat pack phenomenon occurs.

6.2.4 | The role of prior knowledge in NL

All NL is built upon what students already know (National Research Council, 2000), yet not all prior knowledge is equally helpful for making sense of new information (Schwartz & Martin, 2004). For example, when learners possess knowledge that is well-organized around the most central disciplinary ideas, they are more capable of efficiently learning in new situations by discriminating new information, choosing what is relevant, and understanding the new context in terms of their existing cognitive structure (diSessa & Wagner, 2005). In previous work, we have investigated the knowledge networks of students who have participated in the ST and FB units, and we found that students in the ST unit possessed knowledge networks that were more parsimonious and well-connected around the central idea of energy transfer. The knowledge networks of FB participants, on the other hand, included more ideas that were not as strongly linked (Fortus et al., 2019). The results of our qualitative content analysis (Research Question 2) echo the finding that ST students were more likely to activate the core idea of energy transfer, while FB students tended to activate the less powerful idea of thermal energy.

In order for learners to use their existing understanding to make sense of new situations, they must be able to identify deep structures that characterize what is the same across many instances rather than focus on surface features of the new context (Schwartz & Goldstone, 2016). When students use energy ideas to interpret phenomena by labeling various forms, their analysis commonly remains on a more surface level focused primarily on description, and interpreting different phenomena typically involves identifying different sets of energy forms. In addition to identifying energy forms, students in an FB approach also need to use energy transformation and transfer ideas. By requiring so many ideas, often applied at the surface level, a FB approach to energy instruction may not set the stage for students to notice deep structures across phenomena and contexts. On the other hand, students participating in an ST approach learn to consistently interpret a wide range of phenomena in terms of the systems that interact, the direction of energy transfer, and the energy change processes occurring in each system. This simplified analytical framework, which requires fewer ideas and focuses more explicitly on deep structures across contexts, likely set the stage for students to more effectively use their existing knowledge of energy to engage in NL.

6.3 | Assessing NL

A central goal of schooling is to prepare students for functioning effectively when they encounter novel situations outside of school and must engage in NL (National Research Council, 2012). Yet, school assessments largely assess students existing knowledge by asking them to solve problems without access to learning resources—a situation that almost never occurs in real-world situations. To go beyond simply assessing students' existing knowledge and ascertain how this knowledge prepares them to learn about novel phenomena and contexts, assessments must provide learners with access to learning resources (Bransford & Schwartz, 1999).

As we have discussed previously, some assessments of NL are designed by embedding worked examples or written texts into more traditional exams (Belenky & Nokes-Malach, 2012; Etkina et al., 2009; Schwartz & Martin, 2004), while others have followed students through their subsequent school science coursework (Fiedler et al., 2023; Nordine et al., 2011). Other approaches have included eliciting learners initial questions about a novel context (Bransford & Schwartz, 1999) and administering pre/post assessments to pairs of students working through a classroom learning activity (Schneider & Blikstein, 2018).

Each approach to assessing NL has advantages and drawbacks. Embedding worked examples is an efficient way to contrast results among learners who get the example on an exam or not, but hardly represents a real-world learning scenario. Categorizing learners' initial questions is a useful way to evaluate the sophistication of those questions and the initial ideas activated, but this approach does not involve tracking actual learning. Tracking students as they engage subsequent science coursework provides an opportunity to observe NL but requires weeks or months of observation. Administering pre/post assessments is useful for finding evidence of NL during a classroom activity but reveals little about which ideas were particularly useful for NL. We constructed the NPA to both provide evidence of NL and to connect that NL to the initial ideas that students activated.

To design the NPA, we drew upon many of the same learning principles that undergird the design of project-based learning (Krajcik & Shin, 2022). Perhaps most importantly, we recognized that the most effective learning occurs when it is situated in real-world contexts that are meaningful for learners (Blumenfeld et al., 1991; Brown et al., 1989). Thus, learning on the NPA was situated within the context of making sense of a tangible real-world phenomenon that many students had previously seen in their everyday lives (NPA Design Principle 1), even though they had not encountered it during science instruction. Accordingly, new science ideas were introduced in authentic learning resources that students might find outside of the classroom (NPA Design Principle 2), such as a YouTube video, that were specific to the phenomenon under investigation. Such close alignment between the learning context and learning resources supports coherence from the students' perspective, which is key for effective learning (Reiser et al., 2021). By measuring student learning using three-dimensional assessment items (NPA Design Principle 3), the NPA stresses students' active construction of tangible products rather than replication of information provided in the learning resources. This helps to ensure that the NPA measures learning that goes beyond direct recall, and it emphasizes the role of students as active constructors of knowledge as they engage in the practices of science (National Academies of Sciences, Engineering, and Medicine [NASEM], 2019). Finally, the NPA provides explicit opportunities for students to reflect on their prior knowledge and their learning during the task (NPA Design Principle 4). This design element acknowledges the importance of providing students with opportunities to activate and test their own ideas, construct new understandings, and reflect upon their learning (NASEM, 2018). Although we did not use student reflections to construct NPA scores, this element was important to help students in the NL condition process the information from the learning resources and to provide students in the DA condition with opportunities to demonstrate their learning on the assessment.

The design of the NPA is in many ways similar to the design of performance assessments, which are intended to emulate the context in which students' knowledge and skills are actually applied (Lane, 2013). An important distinction is that performance assessments are typically intended to measure how students use their existing knowledge through DA, and they typically do not provide access to additional learning resources. While performance assessments may provide students with opportunities to learn (e.g., by conducting a scientific investigation), performance assessments are designed to provide evidence of how students use their existing knowledge rather than evidence of NL on the assessment itself. The NPA leverages many of the features of a performance assessment to provide meaningful and authentic assessment environment but prioritizes NL rather than application of existing knowledge.

7 | IMPLICATIONS AND LIMITATIONS

7.1 | Implications for energy instruction

Our results suggest that energy instruction plays an important role in how students use their existing ideas to interpret and learn about a novel phenomenon. Specifically, students from the ST unit were more likely to activate the idea of energy transfer when making sense of a novel phenomenon. The idea of energy transfer between systems is particularly powerful in using energy to make sense of phenomena and problems (National Research Council, 2012), yet despite energy transfer being part of the FB unit, FB students were far less likely to activate this idea. This suggests that simply including the idea of energy transfer within typical FB instruction is not sufficient for helping students to use this powerful idea. It may be that prioritizing energy forms in making sense of phenomena promotes labeling at the expense of deeper thinking about energy changes and how they are manifest as systems interact. However, energy forms language is used widely across the sciences and everyday life (Nordine, 2016a), and students need to be prepared for participating with this language. We are therefore loath to advocate for a radical restructuring of K-12 energy instruction to eliminate energy forms/transformation entirely. Further, our study was limited to qualitative energy analysis of a single phenomenon performed by middle school students, and therefore have limited applicability to, for example, how students should learn to use energy to construct computational energy models in high school. Yet, our results reinforce previous research in which we found clear benefits of middle school instruction that prioritizes energy transfers between systems (Fortus et al., 2019; Kubsch et al., 2019, 2021). We therefore argue that middle school energy instruction should emphasize tracking energy transfers between systems, with forms language treated as an earned language shortcut as students engage in more sophisticated analysis in high school and beyond. Such an approach aligns with the Framework and NGSS PEs for energy in middle school and high school, and it may help to alleviate the well-documented challenges that learners experience in applying systems thinking to quantitative energy analysis (Jewett, 2008; Lindsey et al., 2012; Seeley et al., 2019). Whether and how an ST approach in middle school may set the stage for future quantitative energy analysis that incorporates forms language is a question for future empirical research.

7.2 | Implications for assessment

In a research context, the NPA provides researchers with an approach for investigating how students use their existing knowledge to engage in NL. Unlike other published approaches in which opportunities for NL are as limited as a worked example on an exam or as broad as participation in subsequent science courses, the NPA can provide evidence of NL in a single class period. Further, we designed the NPA to align with the principles of learning theory and project-based instruction in order to motivate learner interest, provide authentic learning resources, and to elicit evidence of NL through meaningful three-dimensional science assessments. In this way, the NPA can be useful as a more efficient and authentic way to gather information about how well-prepared learners are to use their existing knowledge to continue learning in the context of real-world situations—which is a core purpose of science learning (National Research Council, 2012; Organisation for Economic Cooperation and Development (OECD), 2018) that is rarely assessed.

In an instructional context, the NPA approach could be particularly useful for formative assessment purposes when embedded within an instructional unit. Administering an NPA at key points in an instructional sequence could provide teachers with important insight about whether and how students use core ideas developed in previous lessons in order to engage with new phenomena and problems, which is a critical component of deep engagement in project-based (Schneider et al., 2020) and storyline units that are designed to be coherent from the students' perspective (Reiser et al., 2021). When used as a formative assessment tool, we believe the DA condition should be eliminated such that all students are in the NL condition. In this way, teachers can gather information about whether and how all students use the core ideas of a unit as they encounter and learn about novel phenomena, and address gaps as necessary. For example, we found that only one student from the FB unit activated the idea of energy transformation in their initial ideas elicited on the NPA, despite this being the most central idea in the FB unit. Knowing that only a few students are activating the most central idea of the instructional unit as they approach new situations, teachers can more explicitly prompt for these core ideas as new phenomena are introduced. Doing this can support deep learning by helping students to use core ideas across contexts (Schwartz & Goldstone, 2016).

7.3 | Summary

This study contributes to a growing literature base by providing further empirical evidence of the value of emphasizing energy transfers between systems in middle school energy instruction, and it describes an approach for researchers and practitioners to assess how students use their existing knowledge to engage with novel phenomena and problems.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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