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Supporting Students in Using Energy Ideas to Interpret Phenomena: The Role of an Energy Representation

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Abstract
In the sciences, energy is an important idea to get insight into phenomena, as energy can help to reveal hidden systems and processes. However, students commonly struggle to use energy ideas to interpret and explain phenomena. To support students in using energy ideas to interpret and explain phenomena, a range of different graphical representations are commonly used. However, there is little empirical research regarding whether and how these representations actually support students' ability to use energy ideas. Building on common ways of representing energy transfer, we address this issue by exploring whether, and if so how, a specific representation called the energy transfer model (ETM) supports middle school students' interpretation of phenomena using the idea of energy transfer. We conducted an interview study with $N = 30$ 8th grade students in a quasi-experimental setting and used qualitative content analysis to investigate student answers. We found evidence that students who construct an ETM when making sense of phenomena consider the role of energy transfers between systems more comprehensively, i.e., they reason about hidden processes and systems to a larger extent than students who do not construct an ETM.

Keywords Cognitive tool · Energy · Middle school · Representation

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Graphical representations are commonly used to support students in learning about energy. Those representations are designed to be actively constructed by students to support their reasoning and as anchors for collaborative sensemaking (e.g., Scherr et al., 2016). In contrast to other central science ideas such as force, there is no consensus representation for energy, and there is little empirical research regarding the actual effectiveness of energy representations in supporting students. While existing representations of energy often emphasize energy as manifest in different forms (Gray, Wittmann, Vokos, & Scherr, 2019), researchers have repeatedly questioned whether forms-based energy instruction is responsible for students' difficulties with energy (Brewe, 2011; Quinn, 2014; Swackhamer, 2005). We investigated whether, and if so how, a specific representation – the energy transfer model (ETM) – that emphasizes the unitary nature of energy instead of forms supports middle school students in using energy ideas to make sense of phenomena in a physical science context.

Background

Energy and Representations

Energy is inherently abstract as it cannot be directly observed or measured. Thus, reasoning about energy relies on conceptual models. When scientists use energy ideas to interpret phenomena, they often use representational tools such as mathematical formulas or Sankey diagrams (Ainsworth, Prain, & Tytler, 2011). When scientists construct such a representation, the specific affordances of the representation can constrain thinking and channel attention in helpful ways. For example, a falling ball can be described through the formula $mgh = \frac{1}{2}mv^2$. The rules of algebra constrain thinking as they only allow for specific manipulations, and attention is channeled towards the variables in the formula and away from surface features such as the color of the ball. However, such expert representations are not accessible in middle school or lower grades when students lack the mathematical foundations. Therefore, other representations such as energy chains (Papadouris & Constantinou, 2016) or pie charts are introduced (see Gray et al. (2019) and Scherr, Close, McKagan, and Vokos (2012) for a review of existing energy representations).

Despite their ubiquitous usage in classrooms, energy representations are rarely a focus of empirical studies. While research often shows examples of students successfully making sense of phenomena while constructing energy representations, it remains largely unknown to what extent constructing the representation supported students.

How Constructing Representations Supports Reasoning

Generally, research has found that active construction of representations supports problem solving and reasoning processes (Ainsworth et al., 2011; Chen, Wang, Grotzer, & Dede, 2018; Kirsh, 2009; Rumelhart & McClelland, 1986). The positive effects of constructing representations can be explained through cognitive and social mechanisms. From a cognitive perspective, active construction supports information processing, e.g., by lowering cognitive load, reordering information, or focusing attention (Mayer, 1997; Paivio, 1986; Rumelhart & McClelland, 1986). From a sociocultural perspective, active construction serves as a hub for shared cognition in collaborative learning environments and stimulates discussion and argumentation during consensus building which can drive inquiry (Barth-Cohen & Wittmann, 2017; Tobin, Lacy, Crissman, & Haddad, 2018; Vygotsky, 1978). Both the cognitive and the sociocultural perspective are embraced when we interpret representations as cognitive tools (Kirsh, 2009). Cognitive tools can be interpreted as all “cultural tools that impose structure on the reasoning process” (Van Joolingen, 1998). To be effective, their use must be carefully integrated with learning activities (Kim & Reeves, 2007).

The structure that cognitive tools impose on reasoning processes when interpreting and explaining phenomena helps students to go beyond their current level, i.e., into what Vygotsky (1978) calls the zone of proximal development. This in turn can then set the stage for future learning, if carefully integrated with learning activities. For example, after tracking forms of energy in pie charts to describe the motion of a pendulum *in a vacuum*, tracking forms of energy in pie charts to describe a pendulum *in air* can lead to a need to account for another form of energy. This can guide further inquiry in pendulums in air and thus set the stage to learn about thermal energy and dissipation.

We consider the perspective of cognitive tools to be fruitful to investigate representations used to support students’ learning about energy, as representations such as energy chains or energy tracking diagrams are designed to (a) be actively constructed and used in a learning environment and (b) support students through cognitive mechanisms such as channeling of attention or constraints in thinking.

As the effectiveness of energy representations depends on their alignment to the learning environment (Ametller & Pintó, 2002; Gray et al., 2019; Kim & Reeves, 2007; Scherr et al., 2012), we describe the learning environment used in this study in the next section and then explain how the used energy representation aligns with it.

Learning Environment and Energy Representation Used in this Study

Traditionally, introductory energy instruction in middle school focuses on forms of energy and transformations between those forms. Informed by the emphasis on energy transfers between systems in leading documents such as the *Framework for K-12 Science Education* (National Research Council, 2012) and similar proposals in the literature (Brewe, 2011; Ellse, 1988; Swackhamer, 2005), we have developed a middle school unit that focuses on the transfer of energy between systems and conceptualizes energy as unitary, i.e., no forms of energy are introduced (for a detailed description of the approach, see Nordine, Fortus, Lehavi, Neumann, & Krajcik, 2018). Following the recommendations in the *Framework for K-12 Science Education* (National Research Council, 2012), systems identify the part of the universe under investigation; thus systems can be single objects, fields, or collections of objects and/or fields. Fields are required in the systems-transfer approach to discuss phenomena that include interaction at a distance without resorting to transformations between energy forms (Nordine et al., 2018). In the unit, fields are not introduced as mathematical abstractions (as they typically are), but as systems that energy is transferred to or from in phenomena that involve interaction at a distance. First evidence suggests that 7th grade students use these ideas successfully (Fortus et al., 2019; Kubsch, Nordine, Neumann, Fortus, & Krajcik, 2019).

To illustrate this systems-transfer perspective, consider the description of a collision between two balls A and B: during the collision, energy is transferred from the system ball A to the system ball B. Ball A undergoes an energy decreasing processes as its speed decreases. In turn, ball B undergoes an energy increasing process as its speed increases. By definition, energy transfer is an exchange of energy across system boundaries. Thus, when one discusses the energy transfer from one ball to another, each ball is implicitly defined as a system.

The description of the colliding balls shows that the key ideas to make sense of a phenomenon from the systems-transfer perspective are systems, processes, and energy transfers. Further, a qualitative notion of energy transfer is implicit in the balanced energy-related processes (one increasing and one decreasing) and the fact that energy is always located in a system, i.e., is not created or destroyed. Thus, a representation that serves as a cognitive tool in the systems-transfer unit should represent the key ideas of systems, processes, and transfers and help to support students' reasoning processes around those ideas. None of the energy representations in the literature represent all of the ideas that are important to the systems-transfer perspective (see Gray et al., 2019; Scherr et al., 2012). Therefore, building on existing ways to represent energy transfer, we developed a new representation called the energy transfer model (ETM).

The Energy Transfer Model

The ETM is designed to serve as a cognitive tool for supporting students in making sense of phenomena in the systems-transfer approach to teaching energy. It grows in complexity throughout the course of the unit as students encounter new energy ideas and make sense of increasingly complex phenomena. In its basic form, the energy transfer model (Fig. 1) depicts two interacting systems (A and B) as boxes, describes the measurable energy related processes that are going on in these systems spelled out in brackets, and represents the energy transfer between the systems as an arrow pointing from one system to the other. Further, the arrow must always point from one system to another, i.e., it cannot start or end in "nowhere," and for every increasing energy process, there must be a decreasing energy process. This emphasizes the qualitative notion of energy conservation that when the energy of a system changes, there has to be another change in energy in some other system (Gray et al., 2019). Thus, the representation should provide support for reasoning through its graphical elements and via rules.

For example, when a student has identified a system, the graphical structure of the ETM prompts the student to think about the process in that system because otherwise the process part of the representation would remain empty. Similarly, the rule that the

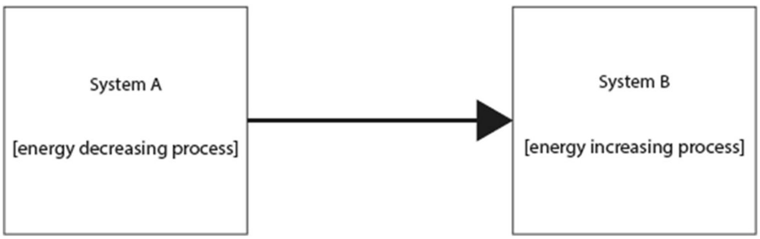

Fig. 1 Base ETM

arrow representing energy transfer always has to connect two systems, forces students that have identified one system with an energy-decreasing process and an arrow pointing away from that system, to think about what the other system to which the energy is transferred might be. By repeatedly using the base ETM to describe a wide range of phenomena, students' thinking should become routinized to look for the key features of interacting systems, energy change processes happening within each system, and the direction of energy transfer between systems.

We refer to this representation as a "model" because in our curricular approach, we use this representation as part of a broader strategy to engage students in the scientific practice of modeling. In the curriculum, students initially create their own models of a phenomenon (a flashlight making a Crooke's radiometer spin), and the basic ETM is introduced through consensus building discussions. In subsequent lessons, students use the ETM to represent key features of varied phenomena as they reason about them, and the ETM is refined and revised throughout the unit as students encounter new energy ideas and increasingly complex phenomena.

Investigating How Constructing an ETM Does Support Students

Despite the widespread use of pedagogical energy representation to support students, their effectiveness is seldom explicitly studied. We lack insight into the effect of constructing energy representations on how students use energy ideas and to what extent these representations guide students' reasoning in supportive ways as the perspective of cognitive tools suggests. However, this is critical when choosing or designing representations that aim at supporting students in applying energy ideas. We address this issue by asking the following research question: How does constructing an ETM support students in applying the systems-transfer perspective to interpret phenomena?

Methods

To address our research question, we conducted an interview study during an enactment of the systems-transfer energy unit. At the point in the unit when the study took place, students had applied the systems-transfer perspective to identify the systems, processes, and energy transfers in numerous phenomena such as collisions, melting ice, interacting magnets, and constructed ETMs for these phenomena. During the interviews, all students were asked to apply the systems-transfer perspective to make sense of two phenomena from everyday life that had not been covered in the unit. Half of the students were asked to use the systems-transfer perspective by constructing an ETM (ETM group), and the other half was simply asked to use the systems-transfer perspective (non-ETM group).

Sample

Two teachers enacted the systems-transfer unit for 10 to 12 weeks in the 8th grade of a rural low-SES middle school located in the Midwestern USA. To avoid teacher effects, a sample of $N = 30$ students from the teacher teaching the most students were interviewed (15% of the total number of 200 students that studied the unit). The teacher was asked to identify six students from each of her five classes who would feel comfortable being interviewed and who represented a range of student achievement levels. To investigate potential selection effects in our sample of $N = 30$ students, we drew on pre- and posttest data originating from a larger project investigating the systems-transfer approach. We compared the gain from pre- to posttest of our sample of 30 students with the whole sample of $N = 200$ students that participated in the enactment of the unit. Further, we compared gain of the ETM group with gain of the non-ETM group. We found similar averages and standard deviations for the ETM and non-ETM group surmounting to a Cohen's $d = 0.08$ ($p = .83$), thus indicating no evidence for a significant difference between the ETM and non-ETM group. Concerning the difference in learning gain between our subsample and the whole sample, we find a Cohen's $d = 0.36$ ($p = .051$), suggesting a possible small difference favoring the interview sample. However, a positive selection is to be expected with students that are willing to be interviewed and is unproblematic with respect to investigating how the ETM supports students but warrants to consider this with respect to generalizing our results.

Interview Protocol

We used a semi-structured interview protocol to ensure that all students received identical initial prompts. Students were interviewed individually. The introductory part (introduction of interviewer, consent, etc.) was always the same. Then we asked the students to explain two phenomena we presented in short videos, 5–10 s long (videos available as online supplemental). In the first video scenario (S1), a golf ball rolls over asphalt and then stops on a small pile of sand. The sand is not visibly moving. In the second scenario (S2), a person releases a basketball from the second floor of a building and the ball falls out of the frame. One group (ETM) was prompted to construct an ETM to explain the phenomena in the videos "How could you use an energy transfer model to explain how the ball moved?". The other group (non-ETM) served as a comparison group. It was prompted to explain the phenomena using energy transfers "How could you use energy transfers to explain how the ball moved?". In both groups noninstructional prompts were used to elicit student ideas, e.g., "How do you know that energy is transferred from the ball?" after a student said that energy was transferred from the ball or "What do the boxes that you have drawn represent?" after a student drew boxes in an ETM. We set up the interview situation such that all students from both groups had access to a pen and paper which they could use to draw an ETM if they desired. Further, we did not require the students from the ETM group to draw; rather we simply asked how they could use an ETM to explain what they saw in the videos.

Interview Scenarios

In Scenario 1 (S1), a rolling golf ball comes to rest on a bed of sand. From the systems-transfer perspective, when the ball system slows down when it comes in contact with the sand, there must be an energy transfer from the ball system to another system. Since the ball slows down when it comes in contact with the sand, the ball is interacting with the sand, and the sand must be the second system. Since energy is transferred to the sand system, it must undergo an energy-increasing process, such as "heating up." However, such a process was not clearly visible in the video but "hidden." Consequently, students had to infer that process. At the point in the unit when the study took place, students had learned about energy transfers in collisions between objects. However, they had not encountered "hidden" processes so far. Thus, S1 is basically a classical near (cognitive) transfer task with the added element of a "hidden" process.

In Scenario 2 (S2), a person drops a basketball which is released from rest and falls out of the frame. From the systems-transfer perspective, there are two systems involved, the ball and the Earth/ball gravitational field. As the ball's speed increases while it is falling, energy is transferred to the ball system from the Earth/ball gravitational field system as the distance between the ball and the Earth decreases. The study was conducted just after the students had learned about magnetic fields but before they learned about gravitational fields. Thus, students had not yet been taught that gravity is mediated by a field which functions as a system capable of energy transfer. Further, the Earth/ball gravitational field system is not visible.

Thus, S2 is situated farther away in the students' zone of proximal development than S1. This setting allows us not only to explore to what extent the ETM supports students to make sense of a phenomenon with a "hidden" system but also to what extent the ETM helps to set the stage for future learning, i.e., to what extent can the phenomenon of the basketball speeding up without any apparent energy transfer to it establish a need to know that the next lessons of the unit could address.

As we discussed in the background section, cognitive tools should do two things: first, support students to do better and second, generate insights that can guide further inquiry in a learning environment. The first aspect is primarily addressed by the near transfer S1 and the second by S2 which has a forward-looking component with respect to the unit.

Analysis

For the analysis of the interviews, we first transcribed all audio recordings of the interviews. The students from the ETM group drew the ETMs with a smart pen. A smart pen is a pen that on top of functioning as a usual pen digitally records as a "video" of what is being written or drawn with it. This allowed us to connect students' drawings with their explanations, i.e., we know how their words correspond to their drawings.

To answer our research question "How does constructing an ETM support students in applying the systems-transfer perspective to interpret phenomena?", we first analyzed how successfully students used the systems-transfer perspective to make sense of the two scenarios. In a second step, we looked for qualitative features that revealed how students used the systems-transfer perspective when reasoning through the phenomena.

How Successfully Do Students Apply the Systems-Transfer Perspective?

We followed a deductive approach to assess to what extent students identified the elements of the systems-transfer perspective in their accounts of the phenomena. Figure 2 shows a sample answer for Scenario 1 using the systems-transfer perspective with and without an ETM.

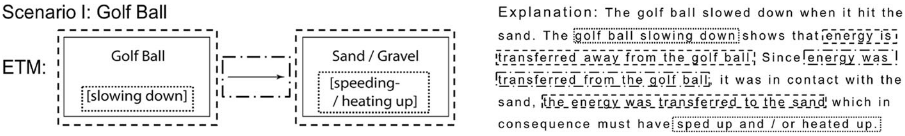

Fig. 2 Correspondence between ETM (left) and non-ETM explanation (right)

For each element in the ETM, there is a corresponding element for the key ideas of systems, processes, and transfer in the non-ETM account.

In the ETM, the first key idea "systems," i.e., the interacting objects, are identified as the two boxes that are labeled "golf ball" and "sand/gravel" and are part of what is an ETM and thus related to energy. Similarly, in the non-ETM account, the systems are identified when the two objects are related to processes or energy transfers and thus the systems-transfer perspective. ETM group students cannot just write "ball" somewhere on the page to demonstrate that they identify interacting systems but have to write "ball" in a box that is clearly part of an ETM. Students in the non-ETM group cannot just say "ball" but have to use it in a discourse that features the elements of the systems-transfer perspective, e.g., "the sand and ball are the two interacting systems here."

To identify the second key idea "processes" that are going on in the respective systems, ETM group students have to write "slowing down" in a box labeled "golf ball," and non-ETM group students have to say something similar to "the golf ball slows down" in a way that relates the statement to the other elements (systems, energy transfer) of the systems-transfer perspective. For ETM students, it is not enough to just write "slowing down" somewhere on the page, but it has to be in the right spot within an ETM. Similarly, students that apply the systems-transfer perspective without an ETM cannot just describe the phenomenon and get credit but have to talk about the processes such as "slowing down" within a discourse that features the other elements of the systems-transfer perspective.

To identify the direction of the "energy transfer" as the third key idea, ETM group students have to draw an arrow pointing from a box labeled "ball" to a box labeled "sand," and non-ETM group students have to say something similar to "energy is transferred from the ball to the sand."

We used the rubrics in Table 1 and Table 2 to score students' ETMs and interviews.

The interviews were coded by a second coder, and we found satisfactory inter-coder reliability between the coders (Cohen's Kappa $\kappa = 0.87$). After an analysis of the conflicting codes, we were able to resolve those.

Table 1 Scoring rubric used for ETM and non-ETM group for S1

Aspect	NC (0)	PC (0.5)	FC (1)
System sand	No/incorrect system identified	–	Sand/gravel
System ball	No/incorrect system identified	–	Golf ball
Process sand	No/incorrect process identified	Increasing	Speeding/heating up (sand/gravel)
Process ball	No/incorrect process identified	Decreasing	Slowing down (golf ball)
Transfer sand	No/incorrect transfer identified	–	Energy transfer to the sand/gravel system
Transfer ball	No/incorrect transfer identified	–	Energy transfer from the golf ball system*

Table 2 Scoring rubric used for ETM and non-ETM group for S2

Aspect	NC (0) Aspect	PC (0.5)	FC (1)
System gravity	No/incorrect system identified	Gravity	Earth/ball gravitational field
System ball	No/incorrect system identified	–	Basketball
Process gravity	No/incorrect process identified	Gravity pulling/increasing	Earth/ball getting closer together
Process ball	No/incorrect process identified	Decreasing	Speeding up
Transfer gravity	No/incorrect transfer identified	Energy transfer from gravity	Energy transfer from the Earth/ball gravitational field
Transfer ball	No/incorrect transfer identified	–	Energy transfer to the basketball

We applied the same scoring rubric to both groups because in both conditions, students have equal opportunity to represent the systems, processes, and transfers they identified. In both scenarios, a number of students used "increasing" and "decreasing" to refer to increasing or decreasing energy processes in the systems which we scored with a partial credit as it is ambiguous and imprecise. In S2, we found that a number of students mentioning an energy transfer from "gravity" instead of from the "Earth/ball gravitational field." As the idea of a gravitational field was new to students, we awarded this answer a partial credit.

Qualitative Features in How Students Apply the Systems-Transfer Perspective

We complimented the deductive approach using an inductive approach based on Mayring (2014) in which we looked for themes in students' reasoning not captured by the deductive scoring that emphasized a normative perspective. In the inductive analysis, we used phrases and sentences as coding unit and the complete discussion of a scenario as analytical unit. We examined all transcripts and selected anything that related to energy ideas and reasoning about those ideas. When statements appeared to allude to the same concepts, we used the same code; otherwise we coded those instances with a new code. While doing so, we conceived initial category definitions such as "students are using *friction* as an idea." After our first run through the material, we looked at our codes in light of the category definitions and refined the definitions by adding more detail. Codes that did not match the more precise category definitions anymore were dropped or if fitting, reassigned to a new category. At this point, we had identified four categories in the data: "using energy forms ideas," "using force ideas," "reasoning about hidden processes," and "reasoning about hidden systems." However, we dropped the "using energy forms ideas" category because we only found two students (one from each group) referring to forms ideas ("[…] first there is some kinetic energy […] then it slowed down with friction on the ball.", "Wait, is it kinetic or potential energy that is stored"). While this might be surprising, it is in line with findings presented in (Fortus et al., 2019; Kubsch et al., 2019) and may be interpreted as evidence that students adapt the systems-transfer perspective very well and demonstrate little need for the idea of energy forms.

Based on our revised category system (Table 3), we ran through the material once more inspecting and revising our codes if necessary. After that, a second coder did another coding with the categories. Again, we found satisfactory inter-coder reliability

Table 3 Categories established for the inductive coding

Category	Definition	Anchor example	Borderline case
Reasoning about hidden systems	Questioning their own choice of systems, speculating about systems, and arguing for their choice of a hidden systems	*I wanna say it's gravity but it cannot because it gotta be a physical thing*	*I do not know* etc. without further specification does not count. Further questioning where energy could be transferred also falls into this category
Reasoning about hidden processes	Questioning their own choice of processes, speculating about a process, and arguing for their choice of a hidden process	*I do not really know what to put for the process, for the gravel, because it's not moving or anything*	*I do not know* etc. without further specification does not count
Using force ideas	Students are using force ideas in their reasoning. They reason about interactions such as pushes or pulls between objects to explain the phenomenon	*And then once she let it go, gravity just pulled it down, just took it*	*Friction* and *resistance* are also considered force interactions

(Cohen's Kappa $\kappa = .9$), and after an analysis of the conflicting codes, we were able to resolve them.

How Is the Construction of the ETM Linked to Students Reasoning?

To investigate to what extent the ETM routinizes or constraints thinking, we used the smart pen data to analyze how students constructed the ETMs. We used our recordings to analyze how instances of the categories from the inductive analysis are conditional on how students constructed an ETM, i.e., we analyzed when we coded categories such as "reasoning about processes" relative to how students drew boxes, arrows, etc.

Results

How Successfully Do Students Apply the Systems-Transfer Perspective?

We assessed to what extent students applied the systems-transfer perspective on energy successfully to phenomena by scoring to what extent the students were able to correctly identify the relevant systems, energy transfers, and process in the two scenarios. By adding up these scores for each scenario, we arrived at a score ranging from 0 to 6 for each explanation. Table 4 shows the score distribution for both groups and scenarios. We divided the scores into high (no or only one element not correctly identified), medium (two or three elements not correctly identified), and low (more than three elements not correctly identified). While the number of students that score high is relatively similar in the ETM (11) and non-ETM group (9) for S1, the number of students that score low is considerably smaller in the in the ETM group (1) than in the

Table 4 Number of students that scored low, medium, and high in both groups in S1 and S2

Scenario	Group	Number of students		
		Low	Medium	High
S1 (golf ball)	ETM	1	3	11
	non-ETM	6	0	9
S2 (basketball)	ETM	3	7	5
	non-ETM	5	5	5

non-ETM group (6). Based on a chi-square test, the observed differences between the ETM and non-ETM group reported in Table 4 are statistically significant, $\chi^2(2, N = 30) = 6.77,\ p < .05$.

In S2, student scores are more evenly distributed across the three levels (Table 4), but the number of low scoring students is still smaller in the ETM than in the non-ETM group. However, the observed differences between the ETM and non-ETM group reported in Table 4 are not statistically significant, $\chi^2(2, N = 30) = 8.33,\ p > .05$.

Looking at the sub-scores (Fig. 3) explains why student scores in S2 are generally lower than in S1: Although students learned about magnetic fields, nobody used the idea of a field, and thus students only received partial credits for processes and energy transfer sub-scores of the “Earth/ball gravitational field system” as the right panel of Fig. 3 reveals.

Further, Fig. 3 shows that across both scenarios ETM group students slightly but consistently scored higher than non-ETM group students on the sub-scores. A notable divergence is the “process/sand” sub-score. Here, both groups score relatively low, but while ETM group students scored partial and full credits, non-ETM group students either scored full or no credit. As our scoring guide (Table 2) reveals, no credit means either no or wrong answer. In light of the “process/sand” sub-score being hidden, i.e., not clearly visible process, we took a closer look at that sub-score: we found that all students in the ETM group that scored no credit put down a process that was incorrect, while all students from the non-ETM group that received no credit (12) did so because they did not address the process in the sand at all.

In sum, we see students from the ETM group scoring slightly but consistently higher across both scenarios than students from the non-ETM group. In near transfer S1, most students scored high, but the number of low scoring students

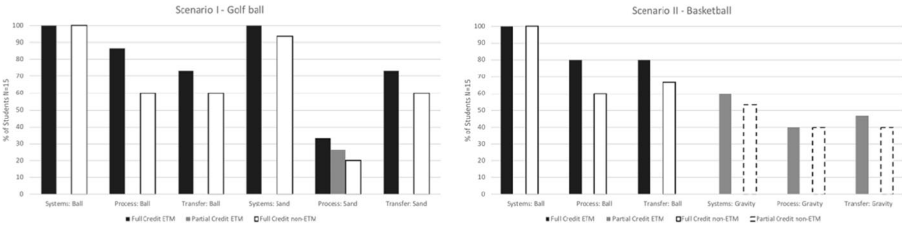

Fig. 3 Distribution of sub-scores for ETM and non-ETM group in Scenarios 1 and 2

is higher in the non-ETM group than in the ETM group. The sub-scores reveal that a majority of students from the non-ETM group failed to address the hidden process in the sand system. In S2, scores were lower on average and more evenly distributed. The sub-scores reveal that this is due to students not transferring the idea of fields successfully. This leads to a limited extent to which our scoring rubric can capture differences in student answers in S2.

Qualitative Features in How Students Apply the Systems-Transfer Perspective

To investigate to what extent students applied the systems-transfer perspective qualitatively different when constructing an ETM versus delivering a non-ETM account, we conducted a qualitative analysis during which we identified three categories (Table 3): using force ideas, reasoning about processes, and reasoning about systems. Further, we noticed that except for one student who verbally described an ETM, no student in the non-ETM group referred to the ETM or chose to use the pen and paper at their disposal to construct an ETM.

Qualitative Features of Student Reasoning

We coded 12 instances in which students used force ideas to explain the phenomena, i.e., they referred to forces as pushes and pulls and tried to connect these ideas to the phenomena:

> "I think it's friction and collision and it slowed it down." (S1)
> "And then, once she let go, gravity just pulled it down, just took it." (S2)

Further, we coded nine instances in which students reasoned about the hidden processes in the sand system in S1 and the Earth/ball gravitational field system in S2. The following examples share that in each case, the student is thinking about a hidden process:

> "I'm thinking about what the sand is doing, because the sand is not increasing, it is just stopping the golf ball." (S1)
> "I just can't think of a process. It's just like pushing it down." (S2)

Finally, we coded another eight instances in which students reasoned about hidden systems, i.e., something like the environment in S1 or the Earth/ball gravitational field system in S2:

> "Because if the gold ball in the sand is decreasing the speed the that means the energy has to be going somewhere" (S1)
> "I wanna say this is gravity but it can't be because it's gotta be a physical thing." (S2)

In sum, the themes we identified were related to students using force ideas to make sense of phenomena and reasoning about the hidden systems and processes in both scenarios.

Distribution of Categories across Scenarios and Groups

Table 5 shows the distribution of the reasoning about hidden systems and processes and reasoning about forces codes across both scenarios and groups. Students in the ETM group reason more about the hidden systems and processes in the phenomena than non-ETM group students. In contrast, non-ETM students reason more about forces than ETM students (five in ETM group seven in non-ETM group).

In the background section, we argued that a key feature of cognitive tools is to provide insights into phenomena that can help students to go beyond their current level and set the stage for future learning. From the systems-transfer perspective, reasoning about hidden systems and processes can be considered such insightful uses. Across both scenarios, Fig. 4 shows the distribution of reasoning about hidden systems and hidden processes for the non-ETM and ETM group. In total, 13 instances of insightful use (76%) are found in the ETM group and 4 in the non-ETM group.

In sum, students from the ETM group use the systems-transfer perspective more often to reason about hidden systems and processes such as the sand heating up in S1 or a hidden system such as air transferring energy to the basketball in S2. Further, although explicitly prompted to use energy-transfer ideas, students from both groups also relied on force ideas – which is not required by the systems-transfer perspective – what more students from the non-ETM than from the ETM group did.

How Is the Construction of the ETM Linked to Students Reasoning?

In S1 we found that the instances of "reasoning hidden processes" we identified in our inductive analysis all happened after students had completed their ETMs expect for the hidden process of the sand. In S2, we found that the instances of "reasoning hidden systems" and "reasoning about processes" we identified in our inductive analysis are also closely linked to the construction of the ETM. After drawing box, arrow, box students filled in the "ball" system and the "increasing speed" process for the "ball" system. Then, they wondered what the other system could be (this is when we coded "reasoning about systems") and after they decided for a system wondered what the respective process could be (this is when we coded "reasoning about processes"). Fig. 5 illustrates this pattern.

Table 5 Distribution of qualitative features in both groups in S1 and S2

Scenario	Group	Number of students		
		Reasoning about hidden systems	Reasoning about hidden processes	Reasoning about forces
S1 (golf ball)	ETM	1	4	2
	non-ETM	1	1	3
S2 (basketball)	ETM	4	4	3
	non-ETM	2	0	4

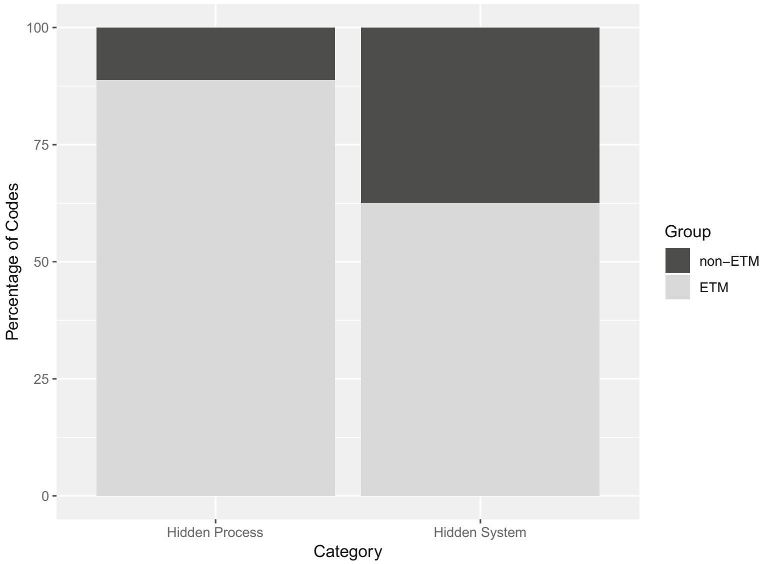

Fig. 4 Percentage of reasoning about hidden systems and processes codes for non-ETM and ETM group

The student first drew the upper ETM, starting with box, arrow, box and then filling in the “ball” system and the respective process “increasing speed.” After putting down “person” and “releasing ball,” the student said: “Well it’s not really getting the energy from the person ‘cause they are just dropping it.” Here, the student questions his choice of processes and in consequence his choice of system, i.e., is reasoning about the involved processes and systems. The student then draws a second ETM below the first one with a “gravity” system and says: “Just can’t think of a process. It’s just like … just like pushing it down.” The student is considering what might be a process for a “gravity” system but does not put any down. However, he is clearly reasoning about a process.

In sum, we found that the 13 instances when students in the ETM group were reasoning about processes or systems were conditional on the construction of the ETM.

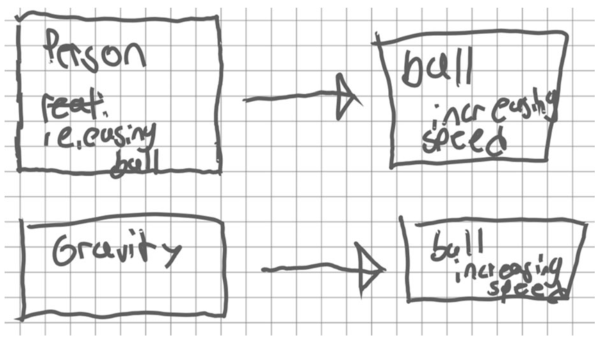

Fig. 5 Illustrative example of an average scoring student

Discussion

We investigated how constructing a specific representation (the ETM) supports students in applying the systems-transfer perspective on energy to interpret phenomena. Our results indicate that students who actively construct a representation as they apply the systems-transfer perspective in a near transfer task (S1) are able to apply it more successfully than students who do not actively construct an ETM. Constructing an ETM seemed to help students to look for hidden processes and systems in the target phenomena and therefore more fully account for relevant energy transfers. A full accounting for energy transfers is necessary to begin developing a sense of energy conservation, and while conservation is not a goal of middle school energy instruction, fully accounting for relevant systems and processes in phenomena helps set the stage for future learning, both within a unit of instruction and over longer periods of time.

A Stopping Golf Ball: How Constructing a Representation Helps Students Full Account for Energy Transfers

We considered the stopping ball phenomenon (S1) a near transfer task as it – unlike any phenomenon encountered by the students before – included a system without any visible process going on. Using a cognitive tool such as the ETM makes it easier to infer the hidden processes and thus do better due to the structure that the construction of the representation imposes on the reasoning process (Chen et al., 2018; Kim & Reeves, 2007; Rumelhart & McClelland, 1986). This helps students to go beyond their current level and into the zone of proximal development (Vygotsky, 1978). The results from our deductive analysis support that students that construct an ETM are more successful in fully accounting for the systems, processes, and energy transfers than students from the non-ETM group: more students from the ETM group than from the non-ETM group score in the “high” category and fewer students from the ETM group score in the “low” category than in the non-ETM group (Table 4). Further, students from the ETM group are more successful in identifying the hidden process than students from the non-ETM group (Fig. 3) that often did not address a process in the sand system at all.

But how did constructing an ETM “imposing structure on the reasoning process”? According to Iiyoshi et al. (Iiyoshi, Hannafin, & Wang, 2005) and in line with the findings from Mayer (1997) and Paivio (1986), cognitive tools can, e.g., help to identify relevant attributes while ignoring irrelevant ones and support learners in connecting new with existing knowledge. The results from our inductive analysis indicate that students from the ETM group are more likely than non-ETM group students to reason about the hidden processes going on in a system – a key attribute of the systems-transfer perspective. In addition, they use fewer force ideas – a concept that is rather irrelevant to explaining a phenomenon from a systems-transfer perspective. When we analyzed how students reasoned through the phenomenon, we found that the instances of reasoning about the hidden process identified in the ETM group were conditional on how students constructed the ETMs, that is, they happened when students were constructing the process part of their ETM. Thus, our results suggest that the ETM functions as a cognitive tool as it helps students to focus on key elements of the systems-transfer perspective while ignoring concepts that are less important in applying the systems-transfer perspective such as forces to which students are known to digress when asked to use energy ideas to interpret phenomena (Chabalengula, Sanders, & Mumba, 2012; Gilbert, Watts, & Osborne, 1982).

Other authors, e.g., Scherr, Close, McKagan, et al. (Scherr et al., 2012), have put forward the theoretical argument that representations emphasizing transfer and thus depicting energy as a quasi-material substance support students in tracking energy successfully. Our results add to the literature as they add empirical weight to these theoretical considerations.

A Falling Ball: How Constructing a Representation Sets the Stage for Future Learning

S2 went beyond S1 in the sense that it not only included a hidden process and system but also had a forward-looking component with respect to the unit where gravitational energy was addressed right after our study; thus it required a more distal transfer than S1. The differences in scores between ETM and non-ETM students were less pronounced in S2 than in S1 (see Table 4 and Fig. 3). This indicates that while the ETM has leverage into the zone of proximal development within the range of near transfer tasks, it is less effective to go further into the zone of proximal development as in S2 where student had to transfer the concept of fields from the domain of magnetic interactions to gravitational interactions.

Further, as in S1, the results from our inductive analysis suggest that in S2, students from the ETM group are more likely to look for hidden processes and systems than from the non-ETM group. As in S1, those instances are found when students were constructing the respective parts of their ETMs. Students from the ETM group were looking for a system that could transfer energy to the ball and also speculating about potential processes in that system, but their answers remained normatively wrong. However, from the perspective of cognitive tools, this is an example of how the structure that cognitive tools impose on reasoning processes interacts with the learning environment as it can set the stage for future learning (Kim & Reeves, 2007; Vygotsky, 1978). For students who have identified that there has to be an energy transfer from some system to the falling ball, subsequent lessons that introduce the gravitational field as the system that transfers energy to the ball will address a need to know. Such a perceived need to know is important for integrating the idea of a gravitational field into students' knowledge structure (Linn, 2006). More generally, this shows that representations such as the ETM can be an important tool in establishing a need to know for students Table 5.

Reasoning About the Hidden System or Process and Qualitative Conservation

When students were reasoning about the hidden systems or processes, they were recognizing that when the energy of a system changes, there has to be another change in energy in some other system. This reflects qualitative conservation, i.e., energy is always successfully tracked across systems, it is neither lost nor appears out of nowhere (Gray et al., 2019). Routinizing this qualitative notion of conservation that energy always has to be *somewhere* is a powerful foundation for building the quantitative notion of energy conservation later. This notion is also featured in the quasi-material model of energy (Duit, 1987) where energy must come from one system and go to another and which has been shown to support students in progressing towards conservation (Kesidou & Duit, 1991). Recently however, Gray, Wittmann, Vokos, & Scherr, (Gray et al., 2019) argued that a representation shows energy conservation only when it explicitly pictures the count of energy units throughout. This quantitative focus appears to dismiss the potential of qualitative conservation that we observed in this study when students were looking for another system because “the energy has to be going somewhere.” We advocate for recognizing that energy conservation can be represented quantitatively as well as qualitatively and that each way can support students in learning about conservation over time. In fact, such a qualitative perspective on energy conservation in middle school aligns with empirical and theoretical learning progressions (Herrmann-Abell & DeBoer, 2018).

Limitations

Due to the limited amount of variability that two scenarios include, we cannot fully rule out that our results are influenced by the scenarios we chose and future studies would benefit from a wider range of scenarios which would allow to draw more general conclusion about when constructing an ETM supports students in making sense of phenomena. However, we carefully selected the scenarios for their deep structure, i.e., hidden systems and processes, and have no reason to believe that the surface structure either imposed additional challenges or provided additional support that could distort our results.

Students in the ETM group were not asked to think aloud, thus we had to infer how constructing an ETM guided their reasoning from the patterns they followed and from spontaneous utterances. In consequence, our analysis might not have captured the full range of ways in which constructing an ETM can guide student thinking when applying the systems-transfer perspective to interpret phenomena and underestimate how often ETM group students reasoned about systems and processes. However, the aim of this study was to compare students that applied the systems-transfer perspective by constructing a representation with students that applied the systems-transfer perspective without constructing a representation. For non-ETM students, especially without extensive training, the think aloud technique might have interacted with applying the systems-transfer perspective verbally and thus inhibited a comparison between the groups.

Lastly, we acknowledge that our sample size is too small to distinguish all differences between ETM and non-ETM groups statistically and future studies would benefit from larger samples. However, our results align with the theory and support each other. For example, our scores show that ETM students scored higher on the hidden sand system sub-score in S1 than non-ETM students. Our qualitative analysis supports and explains this result as it reviled that almost all students that were actively reasoning about the process in the sand system were in the ETM group and did so conditional on the construction of the ETM, i.e., when they tried to fill in the process for the sand system.

Implications

Our study took place in the context of a particular systems-transfer unit and representations need to align with the learning environment to be effective, yet our results are also valuable beyond the systems-transfer perspective as the base structure of the ETM, i.e., boxes representing systems and arrows between boxes representing energy transfers, is common to representations of energy transfer such as energy tracking (Scherr et al., 2016) or PET diagrams (Goldberg, Robinson, & Otero, 2008). Still, future research could investigate the full range of widely used energy representations and also target the relative effectiveness of different energy representations with respect to the different energy aspects, e.g., energy bar or pie charts may both help students to identify the relevant forms of energy in a phenomenon, but pie charts may support the idea of energy conservation more effectively.

Our results indicate that constructing an ETM helps students to apply the systems-transfer perspective successfully, but students may not consciously perceive these benefits themselves, as no student from the non-ETM group used the pen and paper at their disposal to draw an ETM and only one student referred to the ETM at all. This might be an artifact of the interview situation as we did not ask or encourage non-ETM group students to draw but also points to an issue also identified by Karpicke and Blunt (2011): students may lack the metacognitive resources to judge when constructing a representation can be helpful. Thus, it appears worthwhile to spend time in the classroom on reflecting what (cognitive) tools are helpful in which situations: whereas a thermal imaging camera can help to reveal hidden energy transfers (Nordine & Wessnigk, 2016), constructing a representation such as the ETM can lead to inquiry about hidden systems or processes.

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