Mediating elementary students’ mechanistic reasoning in collective embodied modeling activities

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Abstract: This paper explores elementary students’ mechanistic reasoning about states of matter during a series of collective embodied modeling activities. Recognizing students’ mechanistic reasoning in a collective embodied space can be challenging since students’ reasoning is often deeply - yet implicitly - embedded in their interactions. In this paper, we use Russ et al.’s (2008) mechanistic reasoning framework as a guide to identify moments of mechanistic salience for students and draw upon the learning in embodied activity framework (Danish et al., 2020) to map the mediators within the environment that contribute to the production of such mechanistically rich moments.

Introduction

Mechanistic reasoning is a reasoning ability about the causal process that underlie natural phenomena (Russ et al., 2008). Prior studies have explored the potential of embodiment as a way to explore and understand mechanisms (Danish et al., 2017; Dickes et al., 2016; Mathayas et al., 2019). In the present study, we seek to elaborate the potential connections between mechanistic reasoning and embodiment by examining elementary students’ embodied sense-making around mechanism in collective embodied modeling activities using the Science through Technology Enhanced Play (STEP; Danish et al., 2015; 2020) mixed reality (MR) environment.

Students who are participating in a collective embodied model are often moving continuously. Thus, while teachers and experts may recognize mechanisms embedded in those actions and movements, those embedded mechanisms are not always attended to by students who shift their attention and movements from moment to moment. For example, students may move slowly to represent a liquid state of matter without intentionally aiming for an intermediate distance between their enacted particles, nor noticing this as relevant to producing that state of matter. As such, the present analysis focuses on moments when mechanisms are visible in students' interactions to understand how students’ attention to those mechanism is mediated by their interactions. We then ask: how do mediators in a collective embodied modeling activity affect students’ understanding of mechanism within states of matter?

Theoretical framework

Mechanistic reasoning

Mechanistic reasoning, particularly its use to account for dynamics within the natural world, is foundational to the development of students’ scientific inquiry skills (Koslowski, 1996; Russ et al., 2008). In such contexts, mechanistic reasoning is conceptualized by Russ et al. (2008) as the development of ontological and causal descriptions of underlying structures based on prior knowledge, expertise in a domain (diSessa, 1993), and everyday experiences (Keil et al., 1999). While scholarship has proven the value of creating explanations for how a cause brings about an effect (Schauble, 1996), Kuhn (1997) expands on this conception, drawing attention to understanding the ‘broad cause’ of a phenomenon. This framing encompasses not only the association between agents and sequential effects but also the underlying processes of that association thus enabling students to make predictions (Russ et al., 2008). Furthermore, mechanistic reasoning integrates students’ explanations of how unobservable structures and components at the micro-level of a system account with observable changes at the macro-level (Schauble, 1996). Although mechanistic reasoning is considered a high-level reasoning ability, prior studies have demonstrated that young children can be scaffolded to construct and explain the mechanism of natural phenomena in different domains, such as biology (Danish et al., 2017) and ecology (Dickes et al., 2016).

Mediated collective embodied activity

This study is guided by the Learning in Embodied Activity Framework (LEAF; Danish et al., 2020) which expands upon Cultural Historical Activity Theory (CHAT; Engeström, 1999) for embodied learning contexts. LEAF synthesizes individual and sociocultural theories of learning and highlights the role of the body as a valuable learning resource; within LEAF, each mediator in Engeström's CHAT framework (subject, object, division of labor, community, rules, and tools) is analyzed for its role in transforming embodied learning at both individual and collective levels. To privilege the body as a sensemaking resource, LEAF draws on situated simulation theories (Alibali & Nathan, 2012) and body cueing (Lindgren, 2015) at the individual level, merging them into sociocultural context to understand students' engagement in a joint embodied activity. Individual students' embodiment needs to be understood through alignment with others. The present study design was heavily guided by these principles, situating the various elements present as *mediators* of the activity.

Vygotsky (1978) defines mediators as material and/or ideal cultural tools that transform the relationship between a subject (participant) and the object (goal) of their activity. These mediational means are socioculturally situated and have associated constraints and affordances. In our analysis, we view students' experiences in STEP through the lens of *mediated action* (Wertsch, 1981) where students engage in meaningful action and may as a result appreciate the value of the cultural mediators for their action and apply them in later activity. Our goal is to explore what mediators are present in moments when students identify aspects of mechanism and how these mediators contribute to students' mechanistic reasoning. In the present study, an individual student (subject) embodies a water particle (rules) in a space that is tracked and visualized by a simulation (tool) to inquire particle behaviors (rules) through modeling different states of matter (object) with other "particle" students (community). Some students (community) observe their peers' embodied modeling and make inferences (a division of labor) about the impacts of embodiment on the state of matter based on the simulation feedback. Facilitators (community) scaffold students' embodied modeling and regulate students' classroom behaviors.

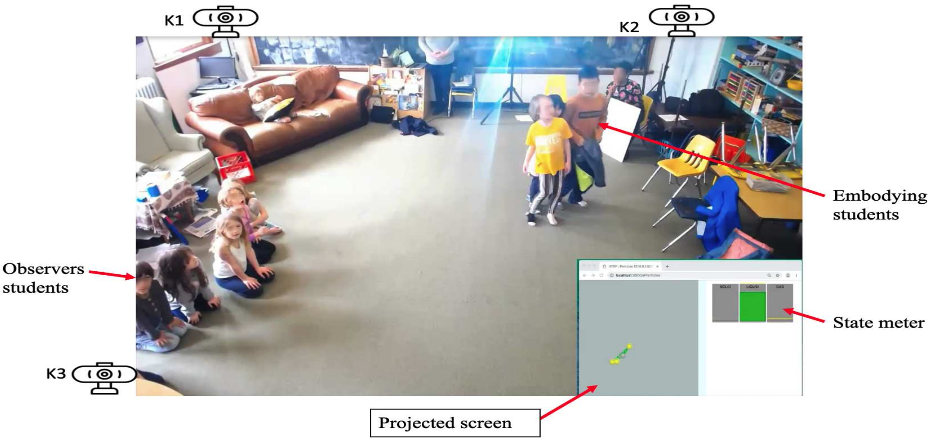
Methods

Design

The present modeling activities occurred using the STEP system, a MR environment for students to explore complex science phenomena (Danish et al., 2015). This curriculum featured 22 first and second-grade students from the Midwest engaging in seven thirty-minute class sessions to explore particles' behavior in three states of matter (Danish et al., 2020). As illustrated in Figure 1, there were three Kinect cameras (labeled K1, K2, and K3) tracking students' movements and projecting them as digital water particles on a projected screen. As students move and interact with each other as particles, their movement and interactions are simulated into different states of matter and displayed through the state meter on the screen.

Figure 1

Students in the STEP MR environment



Data source

This analysis focuses on how mediators in a collective embodied modeling activity contribute to students' collective mechanistic reasoning. We reviewed and contented logged video data across the seven days of the implementation. Next, we identified days three and six as offering the clearest contrast in how students explored mechanisms in exploratory versus more structured activities. During day three, students attended the state meters to indicate how their behavior and collective configurations produced different states of matter. During day six, facilitators asked students to demonstrate their understanding of mechanism by acting out the behavior of particles within predetermined environments as made visible on the projection (pond, ice world, and dessert).

These two class sessions offer us insight into how students engage with mechanistic aspects of states of matter through embodied representations.

Applying Russ et al. (2008) mechanistic reasoning framework to STEP: Particles

In the present study, we draw Russ et al. 's (2008) mechanistic reasoning framework to understand students' reasoning on mechanisms in the context of the state of matter. Russ et al.'s (2008) framework arranges aspects of students' reasoning in a hierarchy based on logical connections and scientific sophistication. These components include (1) description of the target phenomenon, (2) identification of setup conditions, (3) entities, (4) entity activities, (5) entity properties, and (6) the organization of entities that followed mechanistic processes such as (7) chaining, (8) use of analogies, and (9) the use of animated models. We use this framework to characterize students' engagement in mechanistic reasoning through collective embodiment.

In the case of states of matter, we view *the target phenomenon* as the particle behavior that led to the three states of matter (solid, liquid, and gas) in the context of water. An example would be students' commenting on the appearance of a particular state of matter (i.e., "there is a solid") during the embodied activities. We coded *setup conditions* as the moments where students identified the necessary conditions in the environment to produce the phenomenon. For example, students might note that the environment needed to be hot to achieve a 'gas' state. *An entity* in this context was an individual water particle. Students' representations of *properties of entities* included identification of the different speed and attraction strengths of particles in different states. We coded *identifying the organization of entities* when students attended to the difference in distances between particles. *Activities* were coded as an acknowledgement of the various things that an entity engages in; and when students commented on particles' actions (i.e., the use of phrases such as "do," "go," or "move"); for example, when a student commented "let's go into a circle." We coded students' reasoning about changes in a phenomenon as a result of other events elsewhere/at a different scale as *chaining.* An example of (backward) chaining would be students' reasoning that "to make gas, we should move fast."

Data analysis

Two authors collaboratively and iteratively watched video data of the two class sessions through the lens of Russ et al. 's, (2008) framework to identify episodes where aspects of mechanistic reasoning were most salient in students' interactions. Two seven-minute episodes of video data were then selected because they depicted in-depth discussion of mechanism. These were then analyzed to explore how the activity design mediated those discussions. To accomplish this, each video was first segmented into 10-second segments. Authors then jointly coded all of the segments using Russ et al.'s mechanistic reasoning framework as a coding scheme. Next, the first author transcribed the moments with the highest number of mechanistic codes applied into multimodal transcripts. Finally, all authors used interaction analysis (Jordan & Henderson, 1995) to identify how mechanism was being represented through students' interactions, the mediators that contributed to this mechanistic reasoning, and other emergent patterns through iterations of collaborative data sessions.

Findings

The following three cases represent episodes during days three and six of the states of matter unit in which students collectively engaged in mechanistic reasoning about how particles produce states of matter using their bodies. We argue that as mediated action is situated in a particular time and space, that the mediational means present in the classroom function differently in different moments as demonstrated by the ways students do and do not appropriate them. Case one illustrates an episode early in the implementation in which students explored how their bodies could be used to represent particles of a state of matter. Here, verbal and visual cues functioned to productively constrain students' efforts; students realized that appropriate embodiment required attending to particular mechanistic properties of particles. Case two depicts an episode in which students' embodiment did not produce the intended state of matter; facilitators' verbal cues functioned to remediate the activity by shifting students' attention towards why their movements were not working and how to correct them. In case three, we focus on how the STEP system, as a mediator, functions (a) as an instructional organization tool and (b) to simultaneously orient students toward multiple aspects of mechanism at the microscopic and macroscopic level.

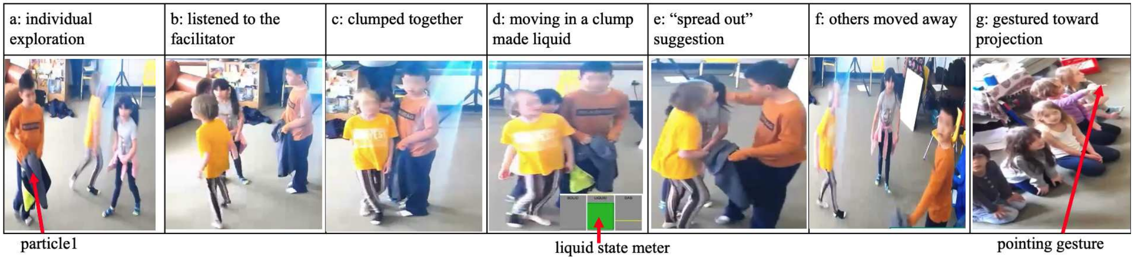
Case 1: Early explorations of state

The following episode was taken from a day three activity in which students are introduced to the concept of particles as related to the state of matter. The activity is exploratory and open-ended; students were not explicitly told that their movement were being mapped onto those of particles; however, through the use of simulation feedback (visual mediation), students came to the conclusion that (a) they were particles and (b) that their proximity to each other was integral to which state of matter was being produced. Table 1 and Figure 2 illustrate this episode.

Table 1
Case 1 transcript

	Actor	**Talk**	**Embodiment**
1	Particles		(Fig 2a) Students wander around individually.
2	Facilitator	What happens when you move together, try to notice something?	(Fig 2b) Three students stop, look at the facilitator, and listen.
3	Particle 1	OK	(Fig 2c) Particle 1 pull other particles together into a tight clump.
4	Facilitator	Instead of running around crazily.	(Fig 2d) All particles move in a tight clump.
5	Observer	Oh, it makes more liquid, the particles go closer together	
6	Facilitator	What happens when they are closer?	
7	Observer	Liquid, more liquid	
8	Particle 1	((hard to hear))	(Fig 2e) Particle 1 points to a farther place and gently pushes the other two students back.
9	Observer	Are they particles?	(Fig 2g) An observer points to the simulation.
10	Observers	They are particles!	All students look at the simulation.
11	Facilitator	Nice, Observer!	

Figure 2
Students' embodied sequence in case 1



Line 1 and Figure 2a shows how students moved around the embodied space individually with few observable indications that they recognized the importance of their movement relative to their peers. The facilitator offered a suggestion (Lines 2 &4) which students accepted as evidenced by how they moved closer together (Lines 3 & 4 and Figures 2c & 2d). This acceptance of the facilitator's suggestion signals that students' conceptions of 'moving together' was heavily related to proximity (speed has been a side-effect). The projected simulation responded to this change in movement by increasing the 'liquid meter' on the graph (Figure 2d) and the observing students shared their realization that this change in movement produced liquid (Line 5 &7). One of the embodying students (labeled 'Particle 1') attended to entity proximity (coded as *the organization of entities*) (Line 8 and Figure 2e) by suggesting that the other embodying students spread out; this suggestion was also accepted as evidenced by their peers moving away (Figure 2f). An observing student inferred that their peers were embodying particles (Lines 9 & 10 and Figure 2g) by gesturing towards the projection of the particle avatars. The rest of the observing students shifted their gaze towards the projection (Figure 2g), exclaimed in agreement (Line 10), and the facilitator expressed approval (Line 11).

This episode demonstrates how facilitators' verbal input and simulation feedback honed students' attention towards mechanistic aspects of the states of matter phenomenon. The combination of facilitator prompts, embodying students' movement as response to the prompt, and real-time projected simulation feedback increases the salience of these mechanistic aspects for students. First, this episode illustrates how students realized that their movements as particles (microscopic *entities*) are connected to which state of matter (the *target phenomenon*) is present. Furthermore, students acknowledged how the phenomenon was determined by the group's collective embodiment rather than individual movement; in this episode, collective embodiment was interpreted as particles distance from one another (*entity organization*).

Case 2: Acting as particles to produce target states of matter

This excerpt portrays a moment from day six (near the end of the unit) where students were tasked with embodying particles at a microscopic scale based on a visualization of the environment at a macroscopic level. A newly introduced mediator - the toggling of a background depicting an icy, pond, or desert environment (Figure 3h) – was disregarded by embodying students despite the target state of matter being continuously mediated by facilitators' questions (Lines 2 through 8). Observing students responded to the failure to embody the target phenomenon by offering a series of recommendations (Line 9). Here, we shift our perspective towards the observing students; we frame embodying students' movement as mediating observing students' engagement with aspects of mechanism such as speed (as a *property* of particles) and distance (*organization of entities*). We offer the following transcript (Table 2) and video sequence (Figure 3) to exemplify the use of students' embodied performances as a mediator for observing students' learning.

Table 2
Case 2 transcript

	Actor	Talk	Embodiment
1	Facilitator	I am going to take particles and transform them into a space, to a setting. And their job is to act like the particles in that setting.	
2	Facilitator	So, what should you guys be?	(Fig 3a & 3b) Particle 1 shows a shivering gesture. Particle 2 holds hands with Particle 1 and Particle 3. Particle 4 wanders in a circle.
3	Particle 2	Uh let's be...solid	
4	Facilitator	So, where are you? Can someone tell me where you are	
5	Facilitator	One of the particles where do you think you are looking at the screen?	(Fig 3c) Particle 4 accepts an invitation to hold hands from Particle 2 & 3.
6	Facilitator	So, Particle 2 said you're going to be solid, why?	(Fig 3d) Particles look at the screen. Particles 1 & 3 walk to the circle center.
7	Particle 2	Uh, we just wanted to be solid	(Fig 3e) Particle 3 leads a "circle dance."
8	Facilitator	You just want to be solid? What setting are you in right now?	(Fig 3f) All particles gaze towards the projection.
9	Observers	You need to be slow and close together	
10	Particle 2	We need to be slow and close together	(Fig 3g) Particles move slowly and closer to each other, accepting Observers' suggestion.
11	Facilitator	How are they doing observers are they making solid? When they are slow and close together?	
12	Observer	Yes, for a second	(Fig 3h)

Figure 3
Students' embodied sequence in case 2

This episode opens with facilitators' attempts to direct embodying students' attention towards the background of the projected simulation (an icy environment as the new *setup condition*) in order to clarify the target state of matter (solid) to the larger group (Line1). Although an embodying student answered (Line 3) with the correct state of matter, it becomes clear that there is a disconnect between why students should be embodying solid water particles; there is no student response to the facilitators several probing questions regarding 'where' the particles are. We interpret this instance (Lines 1 through 8) as embodying students' failure to connect the behaviors of microscopic *entities* (particle movement) to the larger macroscopic *phenomenon* (state of matter): the core causal relationship (coded as *chaining*) within the states of matter content area (as discussed more in Tu et al., 2022). While this failure is indicative of a gap in embodying students' understanding, it functions as a mediational cue for observing students' learning. An observing student proceeded to instruct their embodying peers to be "slow" (a *property* of solid particles) and "close together" (in reference to the *organization of entities*). The embodying students echoed this instruction (Line 10) as an indication that they would accept the suggestion, and the observing students confirmed that a solid was produced (Figure 3h). Here, we see how students' talk and embodiment function as bi-directional mediators for each other's learning. Whereas embodying students' failure to recognize the connection between the simulation's projected background and particle behaviors led to observing students articulating insights regarding the target particle behaviors, observers' verbal scaffolds had a re-mediating effect on embodying students' actions.

Case 3: Embodying the mechanisms linking movement and state

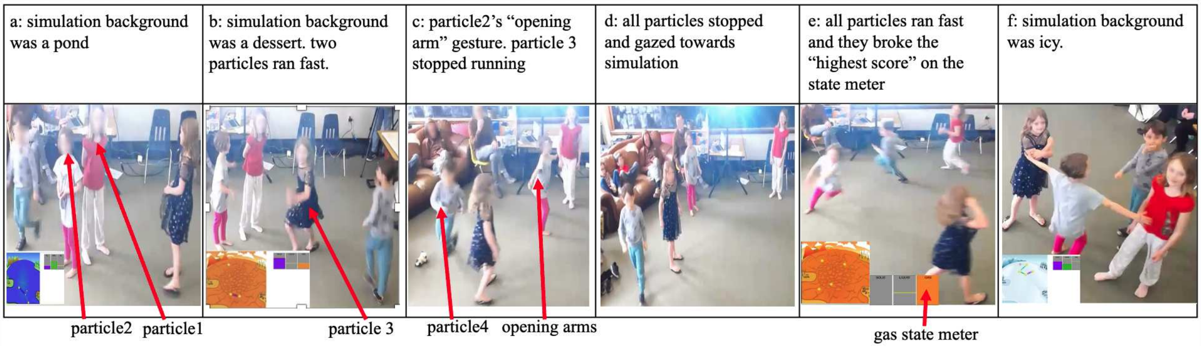
Embodying students continued to explore and began noticing the link between their movement and the simulation's depiction of state. This continued into case three in which students were challenged to quickly adopt the movements of and iterate on their embodied representations to model solid, liquid, and gas states as determined by the background currently visible in the projected simulation (Figure 4). Unlike case two in which embodying students struggled to understand the causal (coded as *chaining*) relationship between microscopic particle behaviors and macroscopic states of matter, case three demonstrates students understanding of not only the relationships between microscopic behaviors and macroscopic states, but the importance of drawing on a multidimensional understanding of particle movement to appropriately represent the target phenomenon.

Table 3
Case 3 transcript

	Actor	Talk	Embodiment
1	Facilitator	I am going to transform you to one more place.	(Fig 4a)
2	Observers	Oh!	(Fig 4b&4c) Two particles begin running fast. Particle 2 suggests "spread out" with an opening arms gesture
3	Particle 2	No, no, no. Spread out	(Fig 4c) Particle 3 stops running and accepts Particle 2's embodied suggestion. Three particles spread out. Particle 4 runs fast.
4	Observers	Run fast!	(Fig 4d) Particle 4 stops running. All particles gaze towards the projected simulation.
5	Observers	Go to gas! Make it go!	(Fig 4e) All particles run fast.
6	Observers	They break the high score ((State meter reached to the top))	(Fig 4e)
7	Particle 2	Wait, let's try to go in a circle ((the facilitator changed the environment back to be icy))	(Fig 4f) All particles stop moving. Particle 3 hugs her arms. Particle 2 organizes students to go back into a circle.

This activity is split into two phases as differentiated by which environment (*setup condition*) was being projected as the simulation background and thus which macroscopic state (*target phenomenon*) students should have been emulating. During the first phase, a group of students embodied particles as the projected background of the simulation changed from a pond (indicating the target state to be 'liquid') to a desert (where the target state is 'gas') (Line 1). Immediately, students responded to this change, however there was a disagreement in which aspects of particle movement were currently relevant; two students started to run to indicate an attention to speed (a *property*) (Figure 4b) whereas another student made a gesture (Figure 4c) to indicate that the group should spread out (*organization of entities*). While both interpretations are appropriate for the desert setting and gas state, the simulation's state meter did not indicate successful representation of gas particles. This failure prompted the embodying students to pause their activity and look towards the state meter (Figure 4d). An observing student suggested that the embodying students all "run fast." The group accepted this suggestion as indicated by their movement, and the state meter indicated the successful representation of gas (Lines 4 -6 and Figure 4e). While the observer's suggestion to "run fast" initially seemed to require that some students compromise on their idea to spread out (attend to distance) in lieu of their peers' idea (to move fast), the outcome of this interaction involved the integrated recognition of multiple aspects of mechanism. In accepting the suggestion and adopting a 'fast' speed, they demonstrated how the embodiment of gas requires that particles both move fast (*property*) and be far apart (*organization of entities*).

Figure 4
Students' embodied sequence in case 3



a: simulation background was a pond

b: simulation background was a dessert. two particles ran fast.

c: particle2's "opening arm" gesture. particle 3 stopped running

d: all particles stopped and gazed towards simulation

e: all particles ran fast and they broke the "highest score" on the state meter

f: simulation background was icy.

The next phase of the activity started immediately afterwards and was indicated to the class by a change to the background environment (to icy Figure 4f). As with the prior phase, students immediately acknowledged the change in environment (the *setup condition*) and recognized that they should be embodying solid particles (the *target phenomenon*) by adopting a new set of movements. They stopped running (to represent slow movement as a *property* of solid particles) and decreased their distance from one another (to represent solid particles as being *organized* closely together) (Line 7 and Figure 4f). The alternating environment (the simulation's background) mediated the activity by functioning as an instructional organization tool; it prompted the entire group to reconsider the requirements of the environment and thus their individual and collective movements. Observers' suggestions scaffolded embodying students' activity by directing attention towards an aspect of particle movement which was currently missing from the embodiment. Here, mediation functions to organize activity based on the macroscopic conditions and make students aware of the multiple intersecting aspects of the phenomenon and particle behavior to successfully represent the target state.

Discussion

This paper explores students' mechanistic reasoning related to states of matter in three collective embodied activities. Mediating students' exploration of different mechanistic properties is an essential part of how classroom teachers and activity systems support this complex reasoning. We notice how mediational means function differently across three different cases; in case one, we see the use of visual and verbal cues to productively constrain students' exploratory movements toward a common objective. Case two illustrates how observing students' talk can be used to scaffold their peers' embodiment as they articulate connections that may not be visible to those 'in' the simulation in a sort of bi-directional mediation. Case three exemplifies how mediation in the form of peer observation and real-time simulation feedback can support students in making connections between mechanistic aspects at both microscopic and macroscopic levels.

We have demonstrated that mediation of collective embodied sense-making to represent scientific phenomena affords students opportunities to engage with aspects of mechanism at both the macroscopic and microscopic levels. Our analysis also indicates the importance of teasing out moments where mechanism is being enacted versus where mechanism is understood. From a teachers' perspective, we suggest that attending closely to students' actions and offering real-time feedback as informed by students' actions can lead to the productive constraining of students' attention towards aspects of the mechanism. From an activity design perspective, we recommend organizing activities to allow for students' embodiment of the target phenomenon in addition to activity observation. This will enable students to articulate the patterns they are noticing in their peers' embodied modeling while their embodied peers leverage this observational talk as verbal mediation. The above cases demonstrate how as students are confronted with various aspects of mechanisms through embodied modeling, mechanistic aspects are compounded and thus simultaneously engaged with during more conceptually difficult activities. Once aware of these multiple aspects, students can more explicitly and maturely attend to the causal relationships and processes that underlie phenomena.

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