IDENTIFYING TEACHING STRATEGIES THAT SUPPORT THINKING WITH IMAGERY DURING MODEL-BASED DISCUSSIONS [1]

This study investigates strategies teachers use to support mental imagery during model-based science class discussions. A microanalysis of videos of classroom discussions was conducted in order to (1) identify and describe teaching strategies for supporting imagery; and (2) identify evidence that the students were engaging in the use of imagery as they constructed models and reasoned about competing models. This study starts from prior work on experts' use of imagery, as well as from prior analyses of imagistic characteristics of concrete exemplars used successfully in a curriculum. Sixteen teacher support strategies for imagery are identified, along with thirteen student imagery process indicators. As the list of descriptors stabilizes, we are also identifying larger categories of descriptors—that is, structured categories of imagistic practices and categories of support. We present examples from a case study based on a transcript of a middle school discussion that served as one of the sources for our new organized set of imagery descriptors.

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Introduction

This paper uses a qualitative analysis of a middle school classroom discussion to illustrate and discuss several categories of teaching strategies and evidence for student use of imagistic processes. In this paper, we identify and describe (1) teaching strategies for supporting imagery, and (2) ways of identifying evidence that students are engaging in the use of imagery. This is not an easy task because imagery is a largely hidden process. Recent literature indicates that mental imagery may provide a foundation for sophisticated types of reasoning in science.

We analyze several classroom episodes to illustrate the strategies. In these episodes, the students discuss two competing explanatory models that were generated by other students to explain some puzzling aspects of human circulation.

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Theoretical Background

Prior Literature

Models are important

In this paper when we say "model," we mean an explanatory mental model, a mental representation of a hidden system that explains a phenomenon. Examples of explanatory models that are "hidden" in the sense that they are difficult to directly observe are: bouncing atoms, spinning planets, blood flowing through capillaries, eroding mountains, reacting molecules, or the pull of gravity on the moon. Windschitl calls these "Big Ideas" (Windschitl, Thompson, Braaten, & Stroupe, 2012).

The NGSS (2013) standards have set goals for students to develop and use models as a key scientific reasoning practice, and include system and system models as one of the cross cutting concepts to be integrated with disciplinary core ideas. Given these advances in national standards, educators are now asking for details about: (a) *strategies for teaching the cross cutting concepts;* (b) *how to teach the components of particular scientific practices;* and (c) *how to integrate these with the teaching of core ideas*. A motivating assumption for us is that if students experience some of the power of scientific reasoning and conceptual understanding, as opposed to only memorized facts, they will experience a higher level of satisfaction and interest in science and will retain more of what they have learned (Duschl, Schweingruber, & Shouse, 2007; Duschl & Grandy, 2008).

A feature central to conceptual understanding is reasoning from explanatory models, e.g., images of colliding gas particles. However, despite important contributions on general learning principles (e.g., Donovan & Bransford, 2005), and contributions on model-based learning (Hestenes, 1996; Lehrer & Schauble, 2000; Raghavan & Glaser, 1995; Linn, Bell, & Hsi, 1998; Lesh & Doerr, 1999; White & Frederiksen, 2000; Spiro, Feltovich, Coulson, & Anderson, 1989; Reiser, Krajcik, Moje, & Marx, 2003; Johnson & Stewart, 1990; Krajcik, McNeill, & Reiser, 2006; de Jong & van Joolingen, 1998; Schwartz & Black, 1996; and others), our knowledge of how to teach visualizable models, and especially of how to guide discussions, is still in a discouragingly primitive state. There are significant contributions on: the incorporation of models into the curriculum (e.g. Johnson & Stewart, 1990; Passmore & Svoboda, 2011), teaching visualizable models in particular (e.g. Smith & Wiser, 2013), lists of strategies and principles for using animations with students (Jones, Jordan, & Stillings, 2001; Mayer, 2003; Lowe, 2003, 2004), tasks for using simulations (e.g. Hieggelke, Maloney, Kanim, & O'Kuma, 2006; Raghavan, Sartoris, Schunn, & Scott, 2005) and on fostering runnable mental models (Hegarty, Kriz, & Cate, 2003), but we have only a handful of studies that provide any practical strategies for prompting students to build visualizable models during real classroom discussions (e.g. Krajcik, Codere, Dahsah, Bayer, & Mun, 2014; Reiser, Berland, & Kenyon, 2012; Schwarz et al., 2009; Windschitl et al., 2012, and colleagues; Louca & Zacharias, 2012). Although Schwarz et al. (2009) identified a learning progression for modeling, our knowledge is limited concerning specific methods of teacher scaffolding to support creating and reasoning with explanatory models of phenomena.

The Nature of Imagery

"Mental imagery" has been defined as "the mental invention or recreation of an experience that in at least some respects resembles the experience of actually perceiving an object or an event" (Finke, 1989, 1990). As used here, a mental image can include any kind of sensory or muscular component, as when imagining pushing or pulling on something.

Imagistic thinking can be learned. Contrary to popular belief, there is limited evidence that students approach learning with well-defined and unchanging learning styles, and little evidence of a connection between visual or verbal learning style and ability to learn with scientific visualizations. There is also little evidence that sex differences in spatial imaging ability can be attributed to a biological cause. There is evidence that some measured sex differences in spatial ability may be due to cultural priming of women that they will do worse on spatial tests. There is also strong evidence that spatial imagery ability is not fixed. Training has been shown to improve both men's and women's ability to reason about imagery involving spatial relationships (Newcombe & Stieff, 2012).

Imagery and Learning

Hegarty (1992), Roth (2001), and Stieff (2011) have investigated imagistic reasoning, mental animation, and the role of gesture in learning, but we lack an organized framework for understanding these processes and know little about how to support them in the classroom. This is of concern, because students and teachers can downplay the role played by mental imagery during the construction of mental models. Researchers have identified a number of potential advantages of using imagistic representations (Schwartz & Heiser, 2006).

Imagery, animation, and imagistic simulation may provide a foundation for more sophisticated types of reasoning in science

Darden (1991) documented nonformal reasoning and model generation, evaluation, and modification processes as important for modeling in genetics. Nersessian (1992) has documented evidence that imagery supported Maxwell's scientific modeling processes. On the basis of think aloud studies of experts, Clement (2009) found evidence that imagistic simulation provided a foundation for more sophisticated types of reasoning which, in turn, underlay generation and evaluation of runnable explanatory models. But the dynamic imagery used in imagistic simulation is hidden; we haven't known how to detect when students are using it.

Previous work on imagery strategies in instruction

Gesture. Alibali and Nathan (2007), Richland (2008), and Roth (2001) have investigated the roles of gesture in teaching and learning. Richland found that mathematics teachers in Hong Kong and Japan, whose students outperformed those in the United States on the TIMSS-R, were more likely than mathematics teachers in the United States to use gestures that physically linked the entities being compared and were more likely to tailor their gesture use to the novelty of the comparison. Clement (2008) reviewed a variety of studies of depictive gestures; these suggest they are concurrent expressions of core meanings or reasoning strategies and not simply delayed translations of speech, justifying their role in providing evidence for the involvement of mental imagery. Several of the imagery indicators derived by Clement (1994) involved gesture, and we will utilize these in the present study.

Drawing. Zhang and Linn (2008) studied how drawing supports learning from external visualizations. They presented evidence that having students draw their ideas after interacting with visualizations can help more than increased time interacting with the visualizations.

We think there are other categories of imagery moves besides gesture and drawing, and we also want to uncover more detail on the ways gesture and drawing are used. We look at how teachers support student use of imagery in the context of model-based teaching and present some evidence that the students were using imagery.

Framework

A companion paper (Clement, 2017) presents a 4-level framework of modeling practices. We include a diagram of two of those levels here as Figure 1.

Clement (2008) studied scientifically trained experts thinking aloud about explanation problems. He found that some of the most interesting solutions exhibited cycles of model generation, evaluation, and modification. That study also identified several nonformal reasoning strategies used by the experts. A study of classroom thinking processes (Williams and Clement, 2015) identified additional reasoning processes. These expert and student reasoning processes are shown at Level 2 in Figure 1. Clement (2008) also identified expert imagistic processes, such as using depictive gestures, imagistic simulation, and imagery enhancement; these are at Level 1. Figure 1 actually represents an expansion of both Levels 1 and 2, resulting from studies of processes in classroom discussions that have added to the original processes detected in expert scientists.

The present study focuses mostly on Level 1, including student imagistic processes and teacher support for student use of imagery, with some attention to nonformal reasoning processes at level 2. In one sense, teacher support moves at the two levels operate at different time scales; a teacher can work to evoke a series of images within a sentence or two, and use these to support a single reasoning process such as evaluating a model for a discrepancy.

The student imagery processes and teacher imagery support strategies we will describe have been consolidated into five emergent categories:

A. Use of mental imagery of a system;
B. Use of animated imagery of a system;
C. Use of scientific drawings to support mental imagery of a system;
D. Use of imagery enhancement that can make imagery of a system easier to think with;
E. Predictive or explanatory imagistic simulation of a system.

Instances of the non-formal reasoning processes often co-occurred with instances of imagery strategies and we note several examples of this.

Purpose

The Next Generation Science Standards (NGSS Lead States, 2013) says, "better mental models … lead to a deeper understanding of science and enhanced scientific reasoning." According to the literature reviewed, dynamic imagery and running mental simulations are at the core of qualitative modeling, and thus central to sensemaking in science. But mental imagery is hidden; we don't know how to detect its use by students. We have the impression that good science

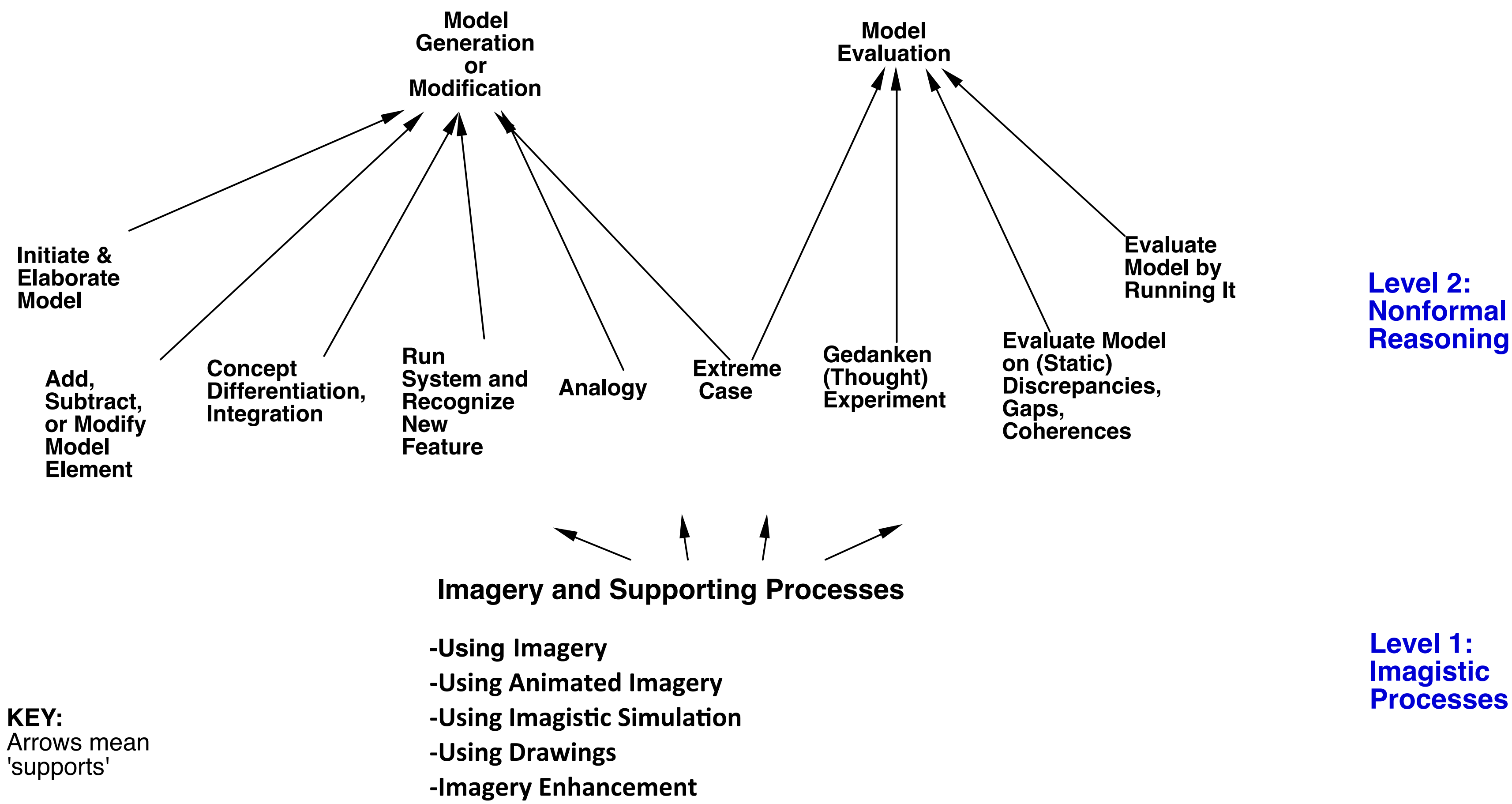

Figure 1. Modeling Practices Framework: Two levels of processes. Each process is associated with a corresponding teaching strategy for scaffolding its use.

teachers know something about how to support their students when they are engaged in imagistic thinking. However, these teaching strategies are implicitly known and unarticulated, and we know very little about how to describe or detect them. We would eventually like to have teacher *guidelines* for how to support imagery processes.

Here, we attempt to:

- summarize, from previous research, a theoretical framework on the importance of imagery in science;
- develop vocabulary and ways of detecting, describing and gaining evidence for imagery use and imagistic processing by students;
- develop vocabulary and ways of detecting and describing imagery support strategies used by teachers;
- illustrate how the evidence for student imagery can coincide with evidence that a student is engaged in reasoning and learning processes.

We will use the framework of imagery processes identified from studies of experts and some preliminary teacher moves identified in our past work, to develop descriptors for:

- scientific imagery processes used by students;
- teaching strategies used to support student use of imagery.

Research Questions

We ask:

- What imagery support moves do teachers use?
- What evidence can we detect for student use of imagery?
- Does evidence of student use of imagery coincide with evidence for their use of nonformal reasoning processes that have been shown to support modeling?

Our Previous Work on Imagery Strategies

Expert work. From analysis of expert protocols, Clement (1994) developed a list of 28 strategies for imagery use. Stephens & Clement (2006) used a simplified version of the expert list and applied it to 19 reports or descriptions of imagery-rich mental simulations: 7 generated by expert scientists past and present; 7 initiated by teachers, tutors, or curriculum developers; and 5 student-initiated.

Clement (2008) developed a multi-level framework for model-based reasoning observed in experts. This led us to ask whether there might be levels of reasoning in model-based classroom discussions.

Exploratory classroom video analyses. Stephens, Clement, & Nunez (2006) conducted videotape analyses of classroom activity and identified characteristics of imagistic cases that teachers introduced in discussion. They found that these were consistent with most of the strategies in the simplified list of strategies from Stephens & Clement (2006). Notably, students, too, appeared to use many of the strategies. These strategies eventually formed the seed of what has become Student Category D.

Curriculum analysis. Stephens & Clement (2007, 2008; in preparation) conducted an analysis of analogous cases used in a model-based curriculum and discovered that the characteristics of many of them were consistent with the list of imagery-enhancement strategies developed from the expert protocols. Videotapes of students reasoning with the analogies were also used. During this analysis, several of the imagery enhancement strategies were revised as support strategies, and a new strategy was identified. These curriculum strategies influenced how we thought about the Teacher Support Strategies.

Method

Video analyses. Our purpose is to develop a coherent set of descriptors for imagery processes and strategies. To develop a larger and more organized framework of strategies at imagistic and other levels, the team has conducted additional video case studies of a number of classroom discussions in different topics. In these, both student use and teacher support of the strategies was observed. In addition to using imagery indicators from the sets of strategies identified in our previous work, open coding was used to identify new imagistic strategies and to develop many new hypothesized categories of teaching strategies.

Consolidating, revising, refining the list into an organized set. Much of the work has involved developing and honing the criteria for each indicator. Especially when trying to identify evidence for student use of imagery, we encountered challenges in translating descriptors derived from expert think-aloud evidence to the kinds of evidence we might see among the noise of an active classroom discussion. A qualitative construct development cycle (Strauss & Corbin, 1998) was employed by analysts working jointly via argumentation to consensus to identify new strategies and revise old ones. Specifically, a constant comparison method (Strauss & Corbin, 1990) was utilized in an effort to develop consistent descriptions of the strategies. This involved an interpretive analysis cycle: segmenting the transcript into individual teacher and student turns as the primary units of analysis; making observations from each segment; formulating a hypothesized construct for, or classification of, the imagery support strategy behind the teacher statement or imagistic process behind the student statement; returning to the data to look for more confirming or disconfirming observations; comparing the classification of the statement to other instances; criticizing and modifying or extending the hypothesized category to be consistent with other instances; splitting or joining categories where necessary; returning to the data again; and so on. This is an appropriate methodology of choice for developing new constructs and associated vocabulary.

In our earlier attempts to identify evidence for student imagery, we relied primarily on the microanalysis of *depictive gestures,* which appear to depict an imaginary image "in the air" near the speaker; these yield one kind of indication that internal, or mental, imagery is being used. In the present project, we have moved well beyond that, developing multi-level descriptors:

- evidence for 13 individual student strategies and 16 teacher strategies;
- sets of descriptors for each individual strategy;
- 5 categories of strategies according to their functions.

We will present one of our case studies of classroom discussions to illustrate the organized set of strategies (Tables 1 and 2). Evidence for almost all of the strategies in the set were identified in the transcript and videotape of the entire discussion, although we do not have room to present the entire transcript here. Rather, we will use several excerpts to illustrate a variety of the strategies. The transcript was also analyzed to identify cognitive strategies at Level 2 (Figure 1). Criteria for these strategies are described in the companion papers Clement (2017) and Williams & Clement (2017). Although we will not go into detail about that level here, we will examine where the Level 2 non-formal reasoning strategies coincided with Level 1 imagistic strategies, and ask whether there is any evidence that imagery was supporting higher level reasoning processes.

The five categories of imagistic processes and support moves that emerged during analysis are presented in Tables 1 and 2 as an advanced organizer for the reader.

Context, Participants, Lesson

Context for the exploratory case study

The transcript is of a science lesson taught by one of the authors in a suburban middle school in a college town in the northeastern US. In a study in a previous year, pre-post gains on conceptual tests of human body concepts for this teacher's classes were many times greater than those for classes in a control group, yielding highly significant pre post gain differences, and he can be considered to be unusually experienced. However, at the time this teaching episode occurred, he had not had any discussions of, or training in, the imagery strategy concepts discussed in this paper. The lesson that is the focus of the present paper was taught in several classes and the transcript is from a class during the second day of the unit. The students sat at tables and turned their chairs as needed to participate in whole class discussion and small group discussions.

The goal of the lesson was to help students build an understanding of why our circulatory system has two large loops, one from heart to body and back, and another from heart to lungs and back. Rather than providing this information at the beginning, the lesson began with a motivating question, "How does oxygen get to the big toe?" Over two days of discussions in small groups and whole class, the teacher used multiple support strategies to help students evaluate their many ideas. By the end, students appeared to be able to visualize the flowing blood and what it needed in order to do its work, and generated on their own some of the physical structures that would be necessary. The instructor's goal was for them to develop a deep understanding of why the cardiovascular system has separate pulmonary and systemic circulatory paths.

The teacher had collected student diagrams at the end of each class on Day 1 so he could select diagrams to use to stimulate discussion on Day 2. Two main student models emerged from the Day 1 idea-eliciting discussion, and neither matched the target model the teacher had in mind. The teacher standardized and re-drew the selected diagrams (Figures 2 and 3) to facilitate the comparison of the two models.

The teacher began the Day 2 discussion by displaying the two models drawn on the blackboard (Model 1 and Model 2, Figure 3). In Model 1, the air goes to the lungs and then to the heart through a tube. In Model 2, the connection between lungs and heart is a blood vessel, but it is not color-coded red or blue**.** Starting the class discussion with diagrams that are not correct was done purposefully. The process of comparing the two model diagrams set up the opportunity to ask students which model "works better" and why.

Table 1: Teacher Imagery Support Strategies

A. Strategies that can encourage use of mental imagery of a system:

1. Describe someone (self or other) using mental imagery:

- describe someone picturing an aspect of the system in their mind;
- describe a remote system as though observing it nearby; or
- describe the (static) case as though someone were inside it.

2. Suggest that students think via imagery, or give them verbal support for having done so:

- suggest that students picture something in their minds or give them verbal support for having done so;
- suggest that students think about a remote scene as though it were nearby or give them verbal support for having done so; or
- suggest that students think about themselves inside the scene or give them verbal support for having done so.

3. Use depictive gestures for shapes or positions (in the system of interest)**.**

4. Request that students use depictive gestures or give them verbal support for doing so.

B. Strategies that can encourage use of animated imagery of a system:

1. Make gestures that indicate motion, concrete changes, or forces in the system (where the system is not visible or is visible only in static form).

2. Suggest that students picture or otherwise sense a scenario in their minds that includes motion, concrete changes, or forces in the system, or can give them verbal support for having done so.

3. Describe the forces or movements of entities in a non-human system as though they were conducted by a person (could be another person, not necessarily oneself)**.**

4. Have students play the roles of different model components and act out their movements.

C. Strategies using scientific drawings that can support use of mental imagery of a system:

1. Make or modify a skeletal drawing or diagram.

2. Request or verbally support students to make or modify a simple drawing or diagram.

3. Make gestures or sound effects either above a drawing or point to a drawing to indicate a non-obvious relationship or hidden concrete feature in the drawing; e.g. features such as: amount, shape, spatial relation, size, color, limit, speed, changes, direction of movement (when not clearly depicted); and doing this 'over' the drawing by pointing to, touching, looking at, or referring to a label or unique new feature in the drawing.

4. Ask a question about a non-obvious relationship or hidden concrete feature in the drawing.

D. Imagery enhancement strategies that can make the imagery of a system easier to think with:

1. Exaggerate aspects of a system (size, perspective, simplicity, or alignment).

2. Mentally add markers on the system that make it easier to imagine changes in the system, or to imagine details that are not being physically perceived.

3. Describe or depict the system as though it were of a size and orientation that could be manipulated in one's hands (contrary to the actual size or orientation of the object, or changed in some way from earlier depictions).

E. Strategies that can encourage predictive or explanatory imagistic simulation of a system:

1. Along with one or more of the strategies above, request or verbally support students to make an explanation involving motion, changes, or forces in a concrete system about why a phenomenon occurred, or make a prediction about what will happen in the system.

Could be prediction of a future state of a system or prediction of behavior in another part of the system. Explanation could be of motion or dynamics, or motion/dynamics could be used to explain or predict structure. Could be reasoning about why something happened (cause and effect in the past). Can't be just structure or notation. The other strategies (A-D) could occur in the same turn, or in the previous or following teacher turn, if the turn is on the same specific topic.

Table 2: Evidence for student imagistic processes

A. Evidence for use of mental imagery of a system:

1. States that s/he is imaging, imagining, or remembering experiencing a sensation, in any sensory modality; e.g. internally "seeing" or "feeling":

- describes picturing an aspect of the system in their mind;
- talks about a remote system as though they are observing it nearby;
- adds themselves or someone else into the scene of a static case.

2. Uses **depictive gesture** for shapes or positions (in the system of interest).

B. Evidence for use of animated imagery of a system:

1. Makes **gestures that indicate motion,** concrete changes, or forces in the system (where the system is not visible or is visible only in static form).

2. Indicates verbally that s/he is imagining motions, changes, or interactions over time in a situation. This can include any sensory mode including Kinesthetic Imagery Reports where the subject reports imagining their own actions or muscular effort.

3. Refers to forces or movements of entities in target situation as if they were conducted by a person (could be another person, not necessarily oneself).

4. Adds themselves into the scene of a dynamic case. If teacher has invited students to imagine themselves inside the case, student statements that they are buying into this will still count.

C. Evidence for use of scientific drawings to support mental imagery of a system:

1. Starts or modifies a part of a drawing (not just adding a label) (does include adding arrows or color coding).

2. Uses depictive gestures or **sound effects** over a drawing for an event in the system under discussion (in apparent effort to animate the drawing).

3. Describes or asks a question about a non-obvious relationship or hidden concrete feature in the drawing; e.g. features such as: amount, shape, spatial relation, size, color, limit, speed, changes, direction of movement (when not clearly depicted); and doing this 'over' the drawing by pointing to, touching, looking at, or referring to a label or unique new feature in the drawing.

D. Evidence for use of imagery enhancement that can make imagery of a system easier to think with:

1. Mentions adjusting aspects of a system (exaggerating size, perspective, simplicity, or alignment), making the system easier to imagine.

2. Mentions mentally adding 'markers' on the system that make it easier to imagine changes in the system or to imagine details that are not physically perceived" by the student.

3. Describes or depicts the system as though it were of a size and orientation that could be manipulated in one's hands (contrary to the actual size or orientation of the object, or changed in some way from earlier depictions).

E. Evidence for predictive or explanatory (imagistic) simulation of a system:

1. Along with one or more of the strategies above, student makes an **explanation** involving motion, changes, or forces in a concrete system, or makes a **prediction** about what will happen in the system.

Could be prediction of a future state of a system or prediction of behavior in another part of the system. Explanation could be of motion or dynamics, or motion/dynamics could be used to explain or predict structure. Could be reasoning about why something happened (cause and effect in the past). Can't be just structure or notation. The other strategies (A-D) could occur in the same turn, or in the previous or following student turn, if the turn is on the same specific topic.

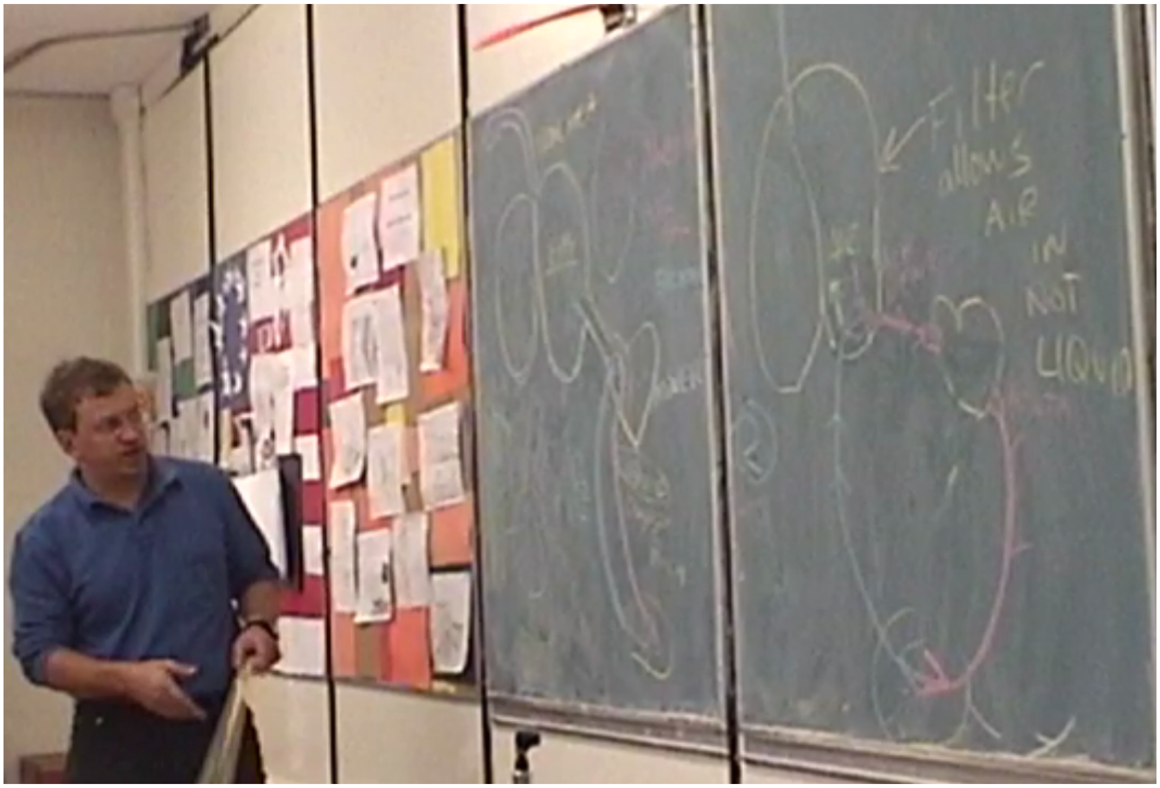

Figure 2: The two models as the students saw them. An enlarged drawing of a capillary bed is just off-screen to the right.

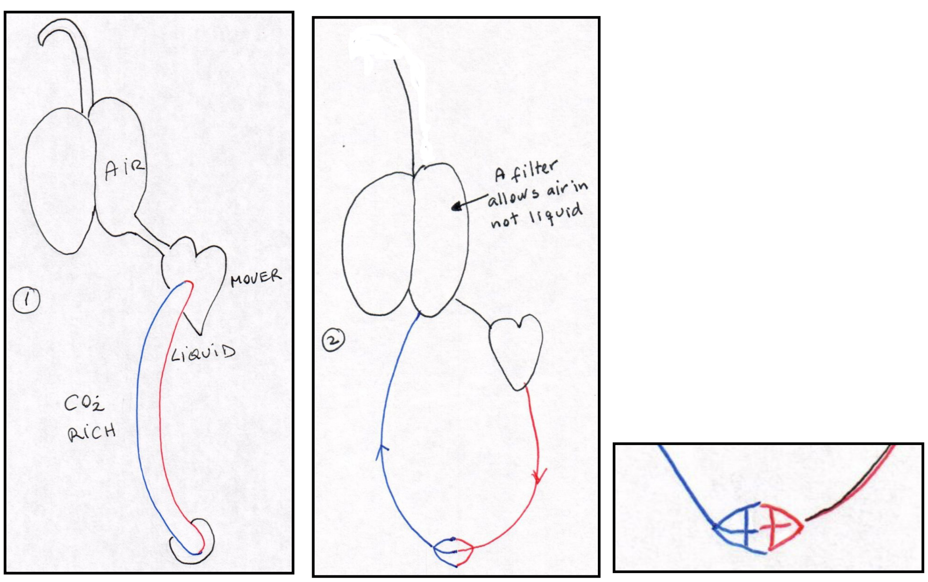

Figure 3: Model 1, Model 2, and close-up of a capillary bed: recreations of the blackboard drawings in front of the class. How does oxygen get to the big toe? (The bottom of each model, where the blue and red lines meet, represents a capillary bed in the toe.)

Classroom Videotape Case Study Evidence

Day 2 began with the students looking at a set of pig lungs and watching a classmate inflate them. After a short break, the teacher moved to the back of the class and stood by a blackboard with Models 1 and 2 drawn on it in colored chalk.

Episode 1

In this episode, the teacher introduces the two models to the class. Important aspects of the models are how blood and oxygen would move through them, and the teacher takes care to make sure the students understand something of the differences between the two models. After this description of the models, he will turn the discussion over to the students, and much of the remainder of the transcript is student dialog. Imagistic processes and support strategies are shown in the third column. The fourth column shows Level 2 non-formal reasoning strategies from Clement's (2017) larger framework. Ellipses indicate light editing to reduce repetition.

		Level 1	**Level 2**
T:	Somebody explained this model to me a little better *(pointing to Model 1)* … The idea is that the [**moving ruler over trachea in drawing]** air comes in, in here **[points to alveoli in lungs],** and we reminded ourselves that air is what state of matter?	B1 motion-indicating gestures C3 gestures over drawing to indicate non-obvious C4 Asks question about non-obvious	Supports or requests students to initiate or elaborate model
Ss:	Air.		
Ss:	Gas.		
T:	Gas, not liquid, right? It is a gas? So it comes in here **[moves the ruler over the Model 1 drawing from the top of the lungs down to the tube that connects lungs and heart, and then to the heart]** and then … this person imagines that it goes to this little tube **[repeatedly moves ruler along a tube drawn between the lungs and the heart]**, … and gets into the heart. And in the heart the blood picks up the oxygen, turns the blood red **[moves ruler along the artery, drawn in red, following it from the heart down to the toe's capillary blood vessels]** and takes it down here to the toe **[points to the toe's capillary blood vessel]** where the toe cells take the oxygen out, put CO2 in, which goes back up to the heart. Ok?	C4 asks question about non-obvious B1 motion-indicating gestures A1 describes someone using imagery C3 gestures over drawing to indicate non-obvious D2 adds markers	Add, subtracts, or modifies model elements

The teacher then describes Model 2 using similar support moves. He points out that, in Model 2, instead of air going through a tube to the heart, oxygen makes a transfer into the blood vessel somewhere in the lungs and then the blood goes to the heart.

T:	So if you had to choose between these two, … You like one where you got a little tube with air, of gas going into the heart **[moves ruler along the tube that connects the lungs with the heart in Model 1]**? Or do we like one where the blood is going into the lung **[T moves ruler over the lungs in Model 2]** and the lung is dropping off the air, and the _blood_ goes to the heart. [*Emphasizing the word "blood,"* **T moves the ruler along the tube that connects the lungs to the heart]**.	C4 asks question about non-obvious B1 motion-indicating gestures C3 gestures over drawing to indicate non-obvious E1 fosters imagistic simulation	Supports or requests students to evaluate a model for (static) discrepancies; Supports or requests students to evaluate a model by running it

In this introduction to the models, the teacher has used strategies from all five imagery support categories. For example, to indicate the path of movement of blood and air in each model, the teacher gestures over the drawings (using a ruler). Each of these utterances supports non-formal model generation and evaluation strategies. Each Level 2 strategy coincides with multiple Level 1 strategies. Note that since we are trying to study the encouragement or use of internal imagery, we are conservative in that we do not count someone simply standing next to a drawing and talking as evidence for use of imagery or support for using imagery. Rather, we count observations such as someone's report that they are using imagery, or someone referring over a drawing to elements (such as motion) that are not visible in the drawing (see Tables 1 and 2).

Episode 2

The teacher has the students break up into small groups to discuss which of the two models they like better. He tells them they will vote on their preferred model later. The small group on camera provided multiple instances that meet our criteria for evidence for use of imagery.

S1:	I say first one, because whenever you see a picture of a heart, there is always, like, the blue side and the red side **[gestures with "blue" and "red" as though pointing to locations in the air]**.	A1 imagery report A2 depictive gesture C3 describes non-obvious	Evaluates a model for (static) discrepancies
S2:	I say second one **[gestures]**.		
S3:	I say second one because it's only the blood that goes into the heart. There's not, like, a channel of air. Otherwise, like, just imagine what happens like when you go get food or something in your lungs.	B2 describes imagining motion B4 adds self into the scene C3 describes non-obvious E1 imagistic simulation	Evaluates a model by running it

In this short excerpt, the students have used strategies from 4 of the 5 categories. (Although S2 appears to have evaluated the models, we did not have sufficient evidence to say that he/she did so via reasoning.) Again, each Level 2 strategy has been accompanied by multiple Level 1 imagery strategies. S3 has identified an unexpected implication for Model 1. This met our criteria for evidence of running an imagistic simulation; the student has made a new prediction for what would happen in the system, and did so while giving evidence of using animated imagery to set the system into motion.

Episode 3

After a few more minutes, the teacher calls the class back together and they vote, with some students voting for each model. He then asks them to go back into their small groups and discuss *why* they like the one they did, and perhaps ask questions of those who like the model they did not like.

S2:	I bet … some of (the models) are kind of right and some of them are kind of wrong.		
S3:	Yeah, you're probably right. Like, it's like, you know how the heart has four chambers? Maybe like, I don't know, maybe like-		Evaluates a model for (static) discrepancies
	[thrusts left hand upward, fingers flat, elbow on table, as though blood moving upward] *(inaudible)* and then it goes **[extends arm above his head, bends hand toward the right as though at the top of an arc]** and then it come **[dives hand downward to the right]** and then it **[moves hand as though tracing a path from the table upward]**, and then goes into one side and then it goes **[continues path across the top of an arc]** into the lungs, and then it picks up **[moves hand back and forth in the air]** whatever in the lungs, **[moves hand back down to the table]** and then comes back.	B1 motion-indicating gestures E1 imagistic simulation	Adds, subtracts, or modifies model elements
S4:	**[As other student was talking, this student had brought her hands together, fingers curled, then straightened her forefingers and crossed them. Then she brought fingertips together with hands cupped. Repeats gestures.]** Zero air goes to the heart. **[She repeats crossed and cupped gestures two more times, for a total of 4x.]**	A2 depictive gestures E1 imagistic simulation	Evaluates a model by running it

We interpreted S3's utterances and gestures as giving a first description of a system with at least two loops going to the heart, unlike either drawing on the board. The very active gesturing appeared to create invisible images in the air, in which blood was moving in differing configurations. We interpreted S4 as criticizing the idea that air goes to the heart, a key feature of Model 1. In the entire 10 minutes of transcript from which these brief episodes were pulled, we identified 21 imagery indicators for students. We infer that these students were able to think imagistically in this teacher's classroom. When student or teacher uses a single Level 2 process, they may be simultaneously using as many as 4 or 5 imagistic processes from multiple Level 1 categories.

It is worth noting that only one utterance with evidence of non-formal reasoning lacked evidence for imagery use. A companion paper, Williams & Clement (2017) discusses the importance of the non-formal reasoning strategies. That study looked at high school classrooms; we find it impressive that these middle school students are engaged in these processes. The fact that Level 1 and 2 processes appeared together in the transcripts—though the levels were analyzed

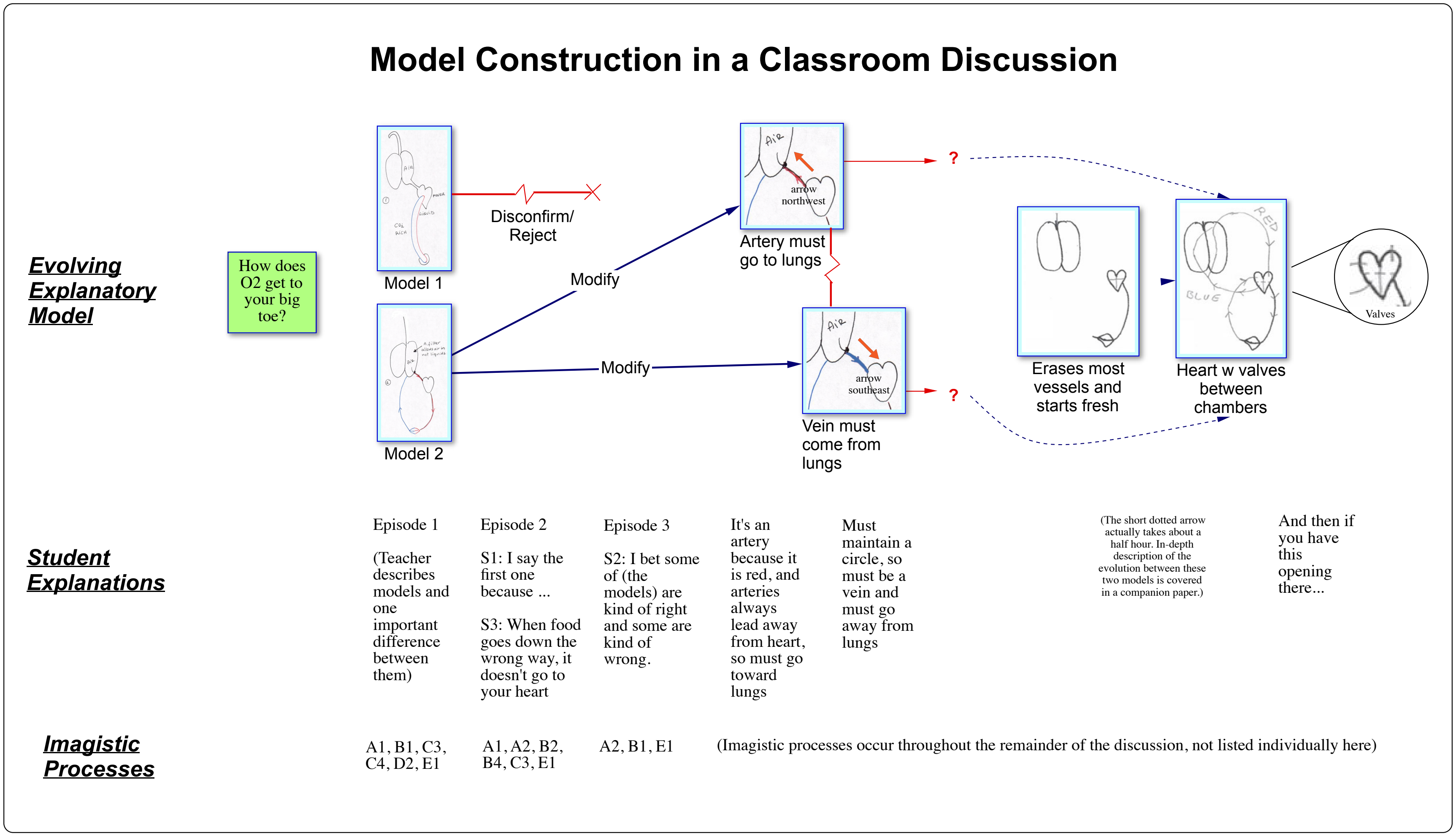

Figure 4. Diagram summarizing the entire classroom discussion.

separately—suggests to us that imagery was significantly involved in supporting the non-formal reasoning in this discussion.

Subsequent Events

During a very active subsequent whole class discussion (Figure 4), much of which has been described in a recent paper (Price, et al., in press), the students and teacher continued to exhibit many of the imagery strategies. Hot topics of discussion included whether both diagrams depicted cycles, because students were sure a cycle was needed. Where all does the oxygen need to go?

During the discussion, when it became clear that students were dissatisfied with both models, the teacher erased all the elements of contention and the students brainstormed what kinds of model elements would work better. Some thought that blood needed to go from the lungs to the heart, and others disagreed, saying that the blood needed to go from the heart to the lungs. Still others pointed out that the heart has four chambers, and there must be some reason for that. One student suggested that perhaps vessels go off in directions not depicted in either model. Eventually they settled on a double-loop model, with one loop going from heart to toe and back, and another going from heart to lung and back. This was very close to the target model the teacher was hoping for. At the end of class, a student spontaneously walked up to the board and erased a small spot between each upper and lower chamber. With that erasure, blood could flow throughout the model (Figures 4 and 5). In Price, et al. (in press), we hypothesize that the student mentally animated the model to see that holes were needed in those two places in order for blood to flow throughout the model.

Figure 5: Recreation of chalk drawing showing holes between upper and lower chambers, the heart "valves" added by a student.

Summary of findings

A major outcome of this study is the set of student imagery indicators in Table 2. In addition, we developed a set of imagistic teaching strategy descriptors in Table 1. In our case study of three imagery-rich episodes from the Heart-Lung lesson, a number of the teacher and student imagistic strategies from those tables were observed:

Teacher:

- A1 describes someone using imagery
- B1 motion-indicating gestures
- C3 gestures over drawing to indicate non-obvious features or relationships
- C4 asks question about non-obvious features or relationship in drawing
- D2 adds markers
- E1 fosters imagistic simulation

Student:

- A1 imagery report
- A2 depictive gesture
- B1 motion-indicating gestures
- B2 describes imagining motion
- B4 adds self into the scene
- C3 describes non-obvious features or relationship in drawing
- E1 evidence for imagistic simulation

These coincided with 4 different teacher support strategies and 3 different student reasoning processes at Level 2, Non-formal Reasoning Processes to Support Modeling. In the passages included here, all four of the student statements with evidence for imagery use (Level 1) were associated with the use of one or more reasoning strategies (Level 2). Conversely, in these episodes, all of the student statements that involved reasoning strategies were associated with evidence for student use of imagery processes.

In addition to the three short excerpts included here, many other episodes of imagery use and support were identified, with 21 student and 25 teacher imagery indicators identified during the 10 minutes of model competition. Among those episodes:

- The teacher modified a diagram of a student model (Teacher C1) in conjunction with depictive gestures (Teacher C3).
- A student pointed to a model on the board and then traced a path in the air with her forefinger as she explained that blood goes to the lungs (Student C2).
- Prediction questions accompanied by motion-indicating gestures over the drawings (Teacher B1, E1) appeared to encourage the students to run mental simulations of the model and to evaluate how the reduction of blood speed would affect the functioning of the model (Student E1).

Discussion

We asked what imagery support strategies teachers use in the context of scientific modeling, and what kinds of evidence we could detect for student use of imagery. We began by summarizing previous research on experts that produced evidence that imagery, animation, and imagistic simulation provide a foundation for more sophisticated types of reasoning in science, which, in turn, underlie generation and evaluation of runnable explanatory models. This motivates the search for imagery support strategies in science education. We have found that the imagery indicators identified in studies of experts have turned out to be useful for identifying student use of imagery. By combining these results with results from a previous classroom study and the present study, the imagery process descriptors have become much more refined and comprehensive, expanding to the 13 student process indicators shown in Table 1. Some of these, such as the use of depictive gestures and talking explicitly about imagery, are fairly obvious, whereas others, such as adding oneself into a scene, and the three strategies in the category of imagery enhancement, are more subtle.

Five major categories have emerged:

A. Use of mental imagery of a system;
B. Use of animated imagery of a system;
C. Use of scientific drawings to support mental imagery of a system;
D. Use of imagery enhancement that can make imagery of a system easier to think with;
E. Predictive or explanatory imagistic simulation of a system.

We saw that evidence for use of imagery occurred along with evidence for use of non-formal scientific reasoning processes in the episodes described here, suggesting the hypothesis that imagery was involved in supporting this kind of reasoning in a significant way. (See also Stephens and Clement, 2010.)

We have also been able to recast these as identifiers for strategies teachers can use to support imagery, shown in Table 2. This is a new accomplishment for us in this article, along with Price, et al. (in press).

Theoretical Implications

The new descriptors in Tables 1 and 2 may make possible further studies of the role of imagery in student learning, as well as the role of imagistic teaching strategies in supporting student learning.

Advantages of imagistic modeling. A runnable imagistic model can serve as a base or building block for improving or expanding the model further. We reported that a student spontaneously built on the class consensus model at the end of the lesson to add valves to the heart. It is very unlikely that he could have detected this problem and repaired it without thinking about the model imagistically, and imagining blood flowing through the model in a mental movie or simulation. This is an example of how imagery-based modeling can lead to further reasoning about a theoretical model and to making improvements in it. Another example was described by Buckley (2000). She found that engagement in model improvement cycles was a key difference between a student who was successful in constructing a mental model and another student who was not, in an instructional setting that shared responsibility for learning with students. Additional examples were identified in case studies of instruction by Steinberg and Clement (1997, 2001) and Clement (2008).

A new theoretical framework for the fundamental role of imagery in model based learning. In the Theoretical Background section, we cited evidence that mental imagery, animation, and imagistic simulation may provide a foundation for more sophisticated types of reasoning in science. We conclude by returning to the theoretical framework in Figure 1, depicting how imagery plays a role in scientific modeling. Although not all aspects of this two level framework are supported by data in this paper, these two levels are part of a larger framework depicted in Clement (2017) for how imagery plays a role in scientific modeling. We do not discuss that entire framework here. However, the present findings are situated within important features of that theory, which is emerging from our larger research program. It is very interesting to us that imagery plays a foundational role in the framework for modeling processes. Imagery and imagistic simulation can underlie all other processes in this framework. In particular, they can underlie the nonformal reasoning processes, which, in turn, underlie model generation, evaluation, and modification. Our case study provides some initial evidence that this framework, which was initiated by expert studies, can be applied to understand student modeling processes in the classroom.

Educational Applications

The Teacher Support Strategies identified in Table 1 are targeted to support the Student Imagery Processes in Table 2. Much of the present work has been to develop descriptors, or classification criteria, that could work with the noise and partial articulations present in transcripts of active classroom discussions. The result has been the identification of 16 imagistic teaching strategies that we believe may be useful in teacher education. These fall into five categories according to their functions: two categories of strategies for encouraging students to actively use mental imagery as a reasoning process (gesturing for, or referring to, static and dynamic imagery); two categories of strategies for making imagery easier to think with (by using drawings or by enhancing the imagery); and a category for encouraging imagistic simulation (by using one of the above strategies along with a request for a prediction or explanation).

Some teachers will find that support for students' imagery is a natural and even unconscious strategy, but others may benefit from being prompted to consciously support their students in creating vivid and animated mental images, especially when students are reasoning about phenomena that are not physically present, or aspects of phenomena not at that moment apprehendable by their unaided senses.

We are particularly concerned that modifiable drawings generated by teachers and students are an underutilized strategy. In the present case study, diagrams provided many benefits in the Heart-Lung lesson:

- They supported lesson planning. Using a diagram during planning, and having the target in mind, lets students run incorrect models, but still lets the teacher have some confidence that he or she will be able to reach the target model of the lesson.
- They supported thinking by providing a static reminder of what the discussion was focusing on.
- They gave the teacher a way to use gesturing to represent an important element of the model being criticized (speed of blood) and facilitated the ability to create a runnable model.
- Drawn on a whiteboard or blackboard, they provided students a *modifiable* picture of the model.

Price, Stephens, Clement, and Nunez (in press) further discuss benefits, to the teacher and the students, of using modifiable drawings and imagery support strategies.

Each strategy in the organized set in Table 1 can be deployed in different ways: the teacher can directly request that students mentally image, can scaffold student use of imagery with more subtle methods, or can model imaging as an important reasoning process. A simple example of a support strategy is for the teacher to use depictive gestures to help students mentally image a shape or an action. Another is to ask students to gesture over a drawing to indicate what is happening in the depicted system. A third example is directly to ask students to use a mental movie of an animated system that they cannot see (such as a group of molecules next to a porous membrane) and predict what would happen next. In particular, the present case study suggests that fostering dynamic imagery and imagistic simulation can be key when running qualitative mental models in science to make confident predictions and explanations that make sense.

Conclusion

Starting from earlier studies of imagistic processes in scientifically trained experts and some from students, we have used classroom videotape case study data to (1) identify evidence that the students were engaging in the use of imagery processes as they constructed models and reasoned about competing models and (2) identify and describe a large variety of teaching strategies for supporting imagery. Sixteen different teacher support strategies for imagery were identified, along with thirteen different student imagery process indicators. These new descriptors in Tables 1 and 2 may make possible further studies of the role of imagery in student learning, as well as the role of imagistic teaching strategies in supporting student learning.

We saw that evidence for use of student imagery processes occurred along with evidence for use of non-formal scientific reasoning processes in the case study episodes described here, suggesting the hypothesis that imagery was involved in supporting this kind of reasoning in a significant way. These findings speak to the most basic levels of a Theoretical Framework for Modeling Practices, shown in Figure 1. In the framework, imagistic processes provide the foundation for higher-level scientific modeling practices. The set of imagery support strategies for teachers identified here provides interesting opportunities for further studies of teaching practices and teacher education.

For companion papers in this symposium by our research group, see:
https://tinyurl.com/knymh39

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