Chapter 5
The Role of Metacognition in Students' Understanding and Transfer of Explanatory Structures in Science

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Introduction

The ability to mentally "step back" and manage how one thinks about and interacts with the world opens up new possibilities for learning and behavior. Reflective capacity moves us beyond merely acting, and reflection at different levels enables new insights, learning, and ability to act in more effective ways in the future. This chapter examines how students' metacognition relates to the likelihood that they will consider their assumptions about the causal structures embedded in scientific explanations and how this correlates with understanding and transfer of the concepts.

Research shows that students tend to use reductive default patterns (Feltovich et al. 1993) in reasoning about science (e.g., Chi 2005; Driver et al. 1985; Grotzer 1993; Grotzer and Basca 2003; Hmelo-Silver et al. 2007; Perkins and Grotzer 2005; Resnick 1994). For instance, they often use a different ontological category—using substance or matter-oriented explanations when process-oriented explanations are warranted (Chi 1992). Or they expect obvious causes and obvious effects, miss effects that involve systems in equilibrium, or those that involve "passive" agents (Grotzer 2004). They assume simple linear, sequential causal patterns with temporal priority between causes and effects (Bullock et al. 1982; Grotzer 1993).

Many science concepts, symbiosis, pressure or density differentials, and electrical circuits, are nonlinear in form involving mutual, relational, or cyclic patterns. They may entail other forms of causal complexity—non-obvious causes; time delays

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and spatial gaps between causes and effects; distributed, unintentional agency; and probabilistic causation where the level of correspondence between causes and effects varies. These forms of complexity are pervasive—part of ecosystem dynamics, global warming, interdependent economies and so forth. Preparing learners to live in a complex world requires helping them learn to be metacognitive about and to reason about such explanatory structures.

Students are typically unaware of their reductive assumptions, and these structural patterns are not addressed by most science curriculum. When extraneous task demands are controlled, even young children can handle some causal complexity (e.g., Kushnir and Gopnik 2007; Sobel 2004). However, causal learning is often implicit, efficient, and subject to the limits of our attention at the moment. In order to move beyond these default assumptions, higher order reflection on the explanatory structure may be needed. Engaging students in activities and discussion designed to reveal the nature of the underlying structure has met with some success in helping students develop deeper understandings of fundamental concepts (e.g., Grotzer and Basca 2003; Perkins and Grotzer 2005).

The Role of Metacognition in Addressing Reductive Assumptions and Encouraging Transfer

A substantial body of research underscores the power of metacognition for enhancing student learning in science. Students who are more metacognitive in their behaviors tend to perform better (e.g., Anderson and Nashon 2006), and when students become more metacognitive, their learning improves (e.g., Baird 1986). Engaging students in metacognitive reflection improves learning in science (e.g., White and Frederiksen 1998, 2000) and beyond (e.g., King 1994; Mevarech 1999; Paris and Jacobs 1984) and results in more permanent restructuring of science ideas (Blank 2000) so that students are less likely to lapse back to earlier, less scientifically accepted ideas. Further, engaging students in metacognition improves the performance of the lowest level achievers the most by helping them manage their thinking (White and Frederiksen 1998, 2000), offering a window into the thinking of peers, by unpacking the structure of the concepts being learned (Perkins and Grotzer 2005), and helping them to learn metastrategic knowledge (Zohar and David 2008; Zohar and Peled 2008). In the study below, we examined whether metacognition might help students to recognize their reductive biases, learn the science more deeply, and transfer it more readily.

Zohar and colleagues (Zohar and David 2008; Zohar and Peled 2008) include the ability to analyze causal relationships as a form of metastrategic knowledge. Metastrategic knowledge refers to "general knowledge about cognitive procedures that constitute higher order thinking skills" (Zohar and Peled 2008, p. 338). In order to effectively deploy particular strategies in particular instances of causation, one first needs an awareness of types of causal patterns and causal features. What is called for is a meta-structural knowledge—the ability to reflect upon and recognize particular forms of causal patterns. It involves detecting the features that make up particular patterns as well as how some of those features make them difficult to detect and to reason about given our human perceptual apparatus. Getting students to reflect upon their causal assumptions and to recognize that they are structuring their explanations in specific ways may be an important step in addressing them.

Most definitions of metacognition include an awareness of cognition as an essential aspect—including both the content of one's own thinking and of one's conceptions (Baird 1986; Hennessey 1999; Kuhn et al. 1988). Hennessey (1999) included active monitoring and attempts to regulate one's cognitive processes toward the goal of furthering learning. Schraw and colleagues (e.g., Schraw 1998; Schraw et al. 2006) focus on knowledge of cognition and the regulation of cognition. They include procedural knowledge, such as note-taking, knowing to slow down for difficult information, etc., as well as conditional knowledge about why or when to use a particular strategy. Evaluation has been key to many definitions (e.g., White 1992). Anderson and Nashon (2006) recently distilled the research to six key dimensions: awareness, control, evaluation, planning, monitoring, and self-efficacy.

Awareness, monitoring, and evaluation (Anderson and Nashon 2006) are perhaps the most critical in realizing one's causal default assumptions and the impact that they have on understanding science concepts. Awareness enables us to detect difficulties in understanding science concepts and to realize how one's default assumptions can distort concepts being taught. Actively monitoring how these assumptions interact with one's science conceptions is critical to transferring understanding beyond the contexts taught and to the real world. Evaluation can play a critical role in choosing the most effective causal framing as students structure new concepts particularly in a conceptual change framework where one is evaluating explanations against the available evidence and trading up for the most powerful explanatory model.

Research (Blank 2000; Georghiades 2000; Hogan 1999; Nickerson et al. 1985) has demonstrated the importance of mental management, or metacognition, as a means to support the restructuring of ideas in science. Metacognitive questions at the intersection of self-awareness and task and/or concept knowledge have been used by others to encourage students to regulate their learning processes in the service of further learning and deep understanding (Beeth 1998a; Blank 2000).

Metacognition should also enhance transfer of concepts. Metacognitive activities engender deeper, more flexible understandings because they are more deeply and actively processed, and these deeper understandings in turn result in more durable or robust concepts which are more readily available for transfer (Blank 2000; Georghiades 2000; Hogan 1999). Blank (2000) included metacognitive "status checks" in terms of how sensible and plausible ideas were as part of a "Metacognitive Learning Cycle" (MLC). She found that classes that used the MLC did not gain a greater pool of content knowledge. However, toward the end of the school year in May, students in these classes revealed significantly greater retention of content.

Perkins and Salomon (1988) distinguish between low road and high road transfer. Low road transfer is reflexive in character—the features of the problem space invite transfer with automaticity (such as driving a mower and a car.) However, the successful mapping and transfer of science concepts to new contexts requires high road transfer—where the learner actively evaluates the fit of the explanatory model and whether it provides a powerful explanation in the given instance.

In earlier work, we engaged students in reflecting upon the nature of the embedded causality in the science that they were learning (e.g., Grotzer and Basca 2003; Perkins and Grotzer 2005). Through activities and discussion designed to reflect upon the embedded causality, students considered the implicit causal structure of the concepts. Awareness of the causal structure was guided primarily by the teacher. The current study attempts to shift responsibility for these reflective behaviors to the students with the hope that it would increase the likelihood of student-initiated transfer.

Three dimensions and related questions were used to frame the metacognitive aspects of the study:

1. Intelligibility: Does the explanation make sense to me?
2. Plausibility: Do I think that the explanation is a possible explanation?
3. Wide-applicability: Can I apply the explanation beyond the contexts in which I have learned it?

These were intended to encourage a focus on one's own thinking, a shift in ownership for learning, and to potentially increase the likelihood of transfer as students were learning about causal patterns in density and air pressure. The first two dimensions were adopted from the teaching of Sister Gertrude Hennessey and written about by Beeth (1998a).

Intelligibility encompasses how students reflect on the sense that their concepts make, as they ask, "Does this make sense to me?" It invites self-initiated *awareness* of their sense-making process and offers a conceptual foundation in which to activate their metacognitive processes. Intelligibility also invites *monitoring* of one's sense-making processes. Too often, students assume that the ideas must make sense to someone—the teacher or other students—but do not actively reflect on whether or not the ideas make sense to them. Assessing the intelligibility of a new idea can also include an interpersonal dimension in addition to an intrapersonal dimension. Students may be encouraged to reflect on other students' ideas, their parents' ideas, or the teachers' ideas. They may learn to ask themselves, "How does the way that this person thinks about the idea help me make sense of it?" However, questions of intelligibility necessarily invite awareness of one's own sense-making.

Plausibility enables students to test their faith in a particular idea vis-à-vis alternative ideas. It is the realm in which students negotiate the status of their ideas, and it invites *evaluation* of the ideas and one's belief in the ideas in terms of their explanatory value. It encompasses the type of metacognition that occurs when students ask themselves, "Should I really believe this idea?" When testing the plausibility of an idea, students may seek counter-evidence against an idea. Students focused on plausibility are often very self-aware of their learning. As a result, they may question the learning and be skeptical of ideas that they only partially understand. Intelligibility and plausibility are important components in deciding whether or not to own an explanation—believability. Ultimately, students need to ask not only whether something is sensible and plausible but whether or not they personally believe it. Students can find an idea plausible but not actually believe it themselves particularly if they find another explanation to be more compelling. An interesting component of plausibility relates to students' recognition of changes in their own thinking, that is, when students say that they used to understand an idea one way and begin to think about the same idea in a different way after witnessing counter-evidence. Often in this case, students' initial ideas may be held simultaneously with the negotiation of new understandings. In this sense, the student assesses their understanding of an idea by comparing their faith in their initial ideas weighed against the new and developing ideas.

Both intelligibility and plausibility complement pedagogies that engage students in modeling. The epistemology of science involves thinking about the explanatory power of a model in terms of the available evidence (e.g., Giere 1988; Hestenes 1992), discarding models that no longer fit, and trading up for more powerful models (Kuhn 1962). Models are a natural extension of classroom discourse in teaching the epistemology of science. Debating and defending models render students' thinking visible (Lehrer and Schauble 2006) to the person espousing the model, other students, and the teacher. Evaluating models for their intelligibility and plausibility is an integral part of discussions in the classrooms studied.

"Wide-applicability" involves connection-making—asking "How can this concept help me in other areas of my learning?" or "What experiences (in class or outside of class) have I had that would help me make sense of this idea?" Wide-applicability is broader in its aims than "fruitfulness," defined by others as part of conceptual change (Beeth 1998b; Hewson and Hewson 1988). As argued by Georghiades (2006), application is only part of the process of transfer. Transfer includes the challenges defined by Gentner (1983)—sensing a structural similarity, mapping from target to base to assess that perceived similarity, deciding where the mapping fits and where it falls down, and actually applying a concept in instances where it is helpful. "Wide-applicability" involves this mapping of the concept against the dimensions of the problem context to figure out where it does and doesn't fit as well as examining its explanatory power beyond the confines of the classroom to understanding in the real world.

The set of three dimensions and framing questions leads to asking a more nuanced set of questions that pertain to both intra- and interpersonal contexts of examining cognition as outlined in Table 5.1. Focusing on these dimensions and asking related questions were referred to as making "metacognitive moves" with the students in the study described below.

The study explored how students responded to the introduction of "metacognitive moves" while learning about the nature of the causal patterns implicit in density and pressure-related concepts. We asked the following questions: (1) What evidence would we find for the types of approaches that students adopted and the ways in which they employed them? and (2) Would there be any evidence that these metacognitive moves may have facilitated transfer of causal understanding between science topics?

Table 5.1 Metacognitive moves: context and characteristic questions

Metacognitive dimension	Context	Characteristic questions
1. Intelligibility	Intrapersonal	Does this idea make sense to me?
		What part of this idea makes sense to me?
		What do I find difficult about this idea?
	Interpersonal	What part of Ian's model makes sense to me?
		What might I add to have it make sense to me?
2. Plausibility	Intrapersonal	Should I believe this idea?
		Does this idea seem likely to be true?
	Interpersonal	Should I believe Ian's model?
		Even if it makes sense to me, is there something about it that seems unlikely to be true?
		What is believable about it?
3. Wide-applicability	Intrapersonal	How can this idea help me in other areas of my learning ?
		Are there pieces of this idea that relate to other ideas I learned about?
		What are the fundamental ways in which they relate?
	Interpersonal	How does Ian's model help me think about other ideas we've talked about?

Infusing Metacognitive Moves in the Classroom

Design

In six eighth grade science classrooms, concepts related to the three dimensions of intelligibility, plausibility, and wide-applicability were infused into "best practices" in science curricula with a focus on using causal forms to deepen understanding for density and air pressure. The best practices included a focus on modeling, active construction of ideas, dynamic computer simulations, Socratic discussion, and being "minds-on." The units also included explicit instruction about the nature of the embedded complex causal forms as described in greater detail below. Each unit was 8 weeks long. The metacognitive support was both materials-based and teacher-facilitated, as described below, and designed to encourage deep learning and to result in greater transfer.

The existing curriculum already included activities designed to increase students' awareness of the underlying causality inherent in the concepts that they were learning. In each of the units, density and air pressure, students needed to grasp an underlying relational causality where a relationship between two things, either balance or differential, accounts for a certain outcome beyond the two things. The density unit incorporated relational causality to explain how density differentials cause something to sink or float, and the air pressure unit engaged students in thinking about pressure differentials involved in a variety of phenomena such as what causes lift, or what causes liquid to go into your mouth when you drink from a straw. This involves a conceptual shift for most students—away from simple linear models ("It is dense so it sinks" or "I suck on the straw and pull the liquid to my lips") to a relational causal model ("The object is denser than the liquid so it sinks in this liquid—but could float in another" or "I create lower pressure in the straw creating an imbalance with the higher pressure outside the straw, so the liquid gets pushed up.").

All students also engaged in explicit discussion designed to help them grasp the underlying causal structures. This discussion unpacked the features of the underlying causality and considered how they differed from simpler models that students were likely to bring to their learning. Examples of the activity sheets that guided this discussion can be found in the appendices. The entire curriculum that was used as a basis for the unit for all students can be found at: http://pzweb.harvard.edu/ucp/. The activities and explicit discussion of causal structures and their features have been shown to significantly enhance students' understanding of the target concepts (e.g., Basca and Grotzer 2001; Grotzer 1993; Perkins and Grotzer 2005). Therefore, these components were held constant in the current study. These aspects of the intervention are, in a sense, metacognitive as they increase *awareness* of the underlying causality embedded in the concepts. As discussed above, awareness is key to realizing one's causal default assumptions and the impact that they have on understanding science concepts.

The metacognitive moves that were assessed in this study were designed to go beyond the teacher's encouragement of students' awareness through the activities and discussion. The moves were designed to shift ownership for the metacognitive components to encourage students to become more aware of their causal assumptions and to encourage greater monitoring and evaluation on behalf of the students. While the actual teaching of the metacognition was supported by materials-based and teacher-facilitated activities, the aim was to encourage students to extend the metacognitive techniques beyond these supports. The research conducted here considers, both qualitatively and quantitatively, metacognitive behaviors that students revealed, how these correlated with transfer of causal concepts, and the extent to which this shift in ownership took place.

Subjects: Students in six eighth grade classes ($n = 182$) participated. The school, in a suburb of Boston, serves primarily middle class families of Caucasian, Middle Eastern, and Indian ethnicities. The classes were taught by two science teachers with three classes of each teacher participating. Pre- and posttest data of students' understanding of science content with embedded causal complexity and metacognitive class level data were collected for all of the students. A subset of three students ($n = 18$) from each class, the primary focus of the results reported below, were interviewed following each unit to assess their understanding of the concepts and their metacognitive behavior. Their writing samples were analyzed in depth.

Class interactions were documented for later analysis of the metacognitive activity. Daily field notes were taken to record observations on in-class dynamics, including metacognitive discussions, the general mindfulness of the class, and major distractions to the class. Explicit teacher–student as well as student–student discussions on the status of ideas and other spontaneous instances of metacognitive activity in class were recorded on a daily basis.

Instructional Materials

The intervention included both materials-based and teacher-facilitated metacognitive support because we expected that teacher-facilitated support would lead to the most conducive classroom culture but recognized that, beyond the context of the investigation, more classrooms would be likely to have materials-based than teacher-facilitated support.

Materials-Based Metacognition

The teaching materials for the unit were infused with questions encouraging students to behave metacognitively. For example, when introduced to what causes differences in density, students were asked to think and write about the intelligibility ("Of what you've learned about what causes differences in density, what makes sense to you? Are there any pieces of what you've learned that seem especially clear to you? What doesn't make sense to you? What pieces seem especially difficult to understand?") (For further examples, see Appendix 1). In addition, posters with questions relevant to the three forms of metacognition were hung around the rooms.

Teacher-Facilitated Metacognition

The units also included explicit opportunities to engage in teacher-guided metacognition. For instance, while students were working on developing models in a group, their interactions were videotaped, and in a subsequent class, students were asked to reflect on what thinking moves they were using and how the moves supported their developing understanding. They also observed and reflected upon whole class videos. As they watched themselves discussing how objects (of different materials) with the same volume could have different masses, the teacher also encouraged students to consider the plausibility of ideas and to connect ideas to other areas of learning (see Appendix 2).

Assessment Tasks of Learning a Metacognitive Behavior

Density and Pressure Written Assessments

Students took a written inventory with ten questions. It included open-ended questions targeting specific difficulties that result in alternative conceptions (i.e., Show and explain the possible outcomes when an object is dropped into a liquid.). It also included multiple-choice questions with responses designed to match specific beliefs that students tend to have about density (i.e., "What happens to the density of an object when you cut it in half?" "Each half of the object is… a. …half as dense as before you cut it. b. …twice as dense as before you cut it. c. …the same density as before you cut it."). These assessments were developed, tested, and subsequently refined in previous work (e.g., Houghton et al. 2000). Some of the density questions were adapted from Smith and colleagues (Smith et al. 1994).

Density and Pressure Interviews

Students were individually interviewed with each interview lasting approximately 30–40 min. Each interview was comprised of open-ended questions focused on a density or pressure-related phenomenon. It was conducted as a structured clinical interview with a series of questions and then a standard set of follow-up probes, such as, "Can you tell me more? I want to understand your whole idea" and "Can you explain in more detail?" Students were invited to draw diagrams or models of their ideas. These interviews were scored for density and pressure understandings and for the student's metacognitive comments, as outlined below. The final section offered scaffolded cueing of the causality involved where students were asked increasingly targeted questions about the nature of the causality involved. If they didn't spontaneously mention causality, they were asked a direct question, such as, "Does what we learned about relational causality help you to think about any of the questions here?"

Assessments of Classroom Interactions

As a means to reveal how students used the moves, we encouraged the use of white boards to model and serve as the basis for both the discussion of and reflection upon their ideas and thinking. These offered informal assessments and were videotaped for later analysis. Students drew models of their initial ideas, enabling us to consider how students used metacognitive moves on an intrapersonal level. Afterwards, they discussed their ideas with class members. The teacher prompted critical debate by asking the class questions such as the following: "What makes sense to you about Ian's model?" "What do you think is confusing about Ian's model?" "Do you believe his model?" "How would you change Ian's model to have it make sense to you?" "How does his model help you think about other ideas we've learned about?"

Daily field notes, videotapes of class discussions, and samples of students' writing provided additional informal assessments of how students used metacognitive strategies on an intrapersonal level and whether they challenged themselves to think metacognitively, whether their reflections on their own thinking changed, and so forth.

Scoring and Analysis

Scoring and Analyzing Students' Metacognitive Comments

Students' metacognitive comments were analyzed through a process of open coding. Two researchers independently evaluated students' comments, the inherent dimensions of each, and the categories that they represented. The overarching categories

Table 5.2 Categories of cognitive and metacognitive strategies

Category	Cognitive or metacognitive strategy
A	Explicit knowledge claim—cognitive statement
B	Explicit knowledge claim + reflective abstract reasoning (*intelligibility*)
C	Explicit knowledge claim + reflective abstract reasoning using "real world" models (*intelligibility + wide-applicability*)
D	Explicit knowledge claim + recognition and reflective exploration of the limitations of their own thinking using "real world" models (*intelligibility + wide-applicability + plausibility*)

were discussed and refined and used to independently score instances of individual and class metacognition.

Individual metacognitive comments were assessed using interview data and writing samples including their science journal entries. To examine the use of metacognitive strategies in class, we open-coded key class discussions around the causally focused activities. Focused on the underlying causal structure, these activities played a key role in exhibiting the strengths and weaknesses of students' understanding and application of causal structures. To explore how metacognition potentially helped facilitate the transfer of causal understanding, 20-min sections of discussion surrounding the same causal activity were videotaped and coded for the number of metacognitive strategies for each class.

Four categories of metacognitive and cognitive strategies emerged in students' comments (See Table 5.2). Metacognitive moves were rarely used in isolation. Students often used a combination of these moves at different levels of sophistication. Notice that these categories are additive in the sense that category B includes the criteria for category A, category C includes A and B, and category D includes A, B, and C. Each student was assigned a score for each metacognitive move and a "Total Metacognitive Score" that was the sum of their metacognitive moves across the categories.

Category A represents cognitive claims or knowledge statements that were not reflective in nature. This type of thinking was explicit in the sense that a student clearly stated what he or she thought, without an awareness of the status of why they thought what they did. It did not fit our working definition of metacognition because it did not involve students' awareness of the content of their own thinking. Nor did it involve actively monitoring the students' own cognitive processes or help students organize their thinking to manage future problems (Hennessey 1999). For example, a student's response using category A when asked, "What do you think causes a hot air balloon to rise?" was "I think that the hot air rises, forcing the hot air balloon to go up. Once it gets cold, it will start to sink (Student #153)." The student did not reflect on the status of why he thought hot air causes the balloon to go up and why the cold air made the balloon sink.

Statements where students backed up their explicit knowledge claims by negotiating the intelligibility of the idea were scored as category B. It included statements where students considered if the idea that they stated truly makes sense to them by thinking it through on an abstract level. This is a fundamental aspect of metacognition. According to Beeth (1998a), a teacher in his study commented that by backing up knowledge claims and overt discussion on how an idea makes sense to students, the students began learning to think "both with their ideas and about their ideas." An example of a category B statement was given when a student was asked if two pieces of aluminum of different volumes have same density. The student responded, "They are both solid pieces of aluminum, but this one has a bigger volume. The other has a smaller volume. This one has a bigger mass. The other has a smaller mass. But I still think that volume for both of them would fit. It's kinda of like this ... let's just say, for example that the volume is 4 cm^3 [the larger piece] and the smaller-sized one is 2 cm^3. The mass of this [smaller one] is 1 g. The mass of this [the larger] is 2 g. The mass of both of them is distributed evenly. Therefore the density must be the same (Student #73)." In this example, the student reasoned himself into understanding that the density of the two pieces of aluminum must be the same because of the outcome of his calculations based on the mathematical equation for density.

Category C combines the sense-making dimension of intelligibility with the connection-making aspect of wide-applicability. The essence of category C involves debating whether or not an idea made sense by placing the idea within a meaningful context. By connecting new ideas to familiar contexts, a student considered whether or not an idea makes sense to him or her. The following response to a question about a piece of steel wool and a solid piece of steel of the same volume was scored as category C. The question was posed, "Do you think they have the same mass?" In response, the student replied, "They used steel for a lot of buildings back before the 50s, so it would be stronger, so it would have to have a greater density to hold up all the weight. But I know that steel wool is sometimes used almost as sandpaper and so it would have to be light, because no one would want to have to carry something that is five or ten pounds across something. So I'd have to say that [solid] steel has a greater mass (Student #70)." In this example, the student made a connection to the practical application of solid steel as a construction material and the use of steel wool as a scouring pad. It was scored as category C because the student considered whether or not the two objects had the same mass by thinking about their function in the real world—using both intelligibility and wide-applicability.

The final category, category D, employed the use of all three metacognitive moves: intelligibility, plausibility, and wide-applicability. Accordingly, students used reflection to push their ideas by making connections and considering alternative explanations for an idea. Students were aware of the fact that they held two different theories to explain one idea. They may have talked their way through the idea through abstract reasoning and connection-making in attempts to determine which idea to believe. Students may also have recognized temporal differences in their thinking. That is, they may have recognized that they held different ideas at different times, perhaps before and after a particular discussion or class activity.

For example, in the pressure interview, a student explained what pressure was and whether it could change in the following response:

> In definition, pressure is just the amount of force put on an object. It's just the amount of force put on an object. Um, the mathematical equation is force divided by area, which would mean if you had 5 Newtons on say, the cassette holder. And that was say, 10 cm^2 or something. Then it would be .5 as the amount of Newtons per cm^2. Other than the definition, the way I think of pressure—I think of in and out as one pressure, instead of having it as pressure one way or the other ... I think that it can change. It all depends on where you are. Like, if you are on Mount Everest, the pressure is obviously going to be extremely low.... If you're at the bottom of the ocean ... you'd have the air pushing down on the water, and you'd have all the water in the ocean pushing down on it, so it would be an extreme amount of pressure. And that's why scuba divers can only go so far ... right at sea level, it's like 15 lbs/in^2.... What I would say it would roughly be, the max, even for the most almost super-human person who could endure so much, I think the max could only be like 19.5. 'Cuz if it's 15 lbs./in^2, a square inch isn't that much, but the extra four lbs. multiplied by, who knows how much, it would be at least a thousand extra pounds on your body. That would mean that there would be a lot pushing out, which would make it really hard to comprehend.

In this example of a category D statement, the student began by providing different ways of thinking about defining pressure. In explaining alternative ways of explaining pressure besides the mathematical formula, the student talked about the "in and out" of pressure. In this sense, he picked up on the idea of pressure differentials as explained as a form of relational causality. By providing an additional definition of pressure besides the mathematical equation, he tested the limits of his understanding by expressing multiple lenses to view the problem (plausibility). He goes on to explain how pressure can change by applying his ideas about pressure in different contexts (wide-applicability). He also talked about pressure in higher and lower situations and the dynamics of how pressure changes between these two extremes. In this way, he tested the limits of his thinking by making connections.

Scoring and Analyzing Students' Causal Understanding in Science Concepts

The written assessments of students' understanding of science concepts were scored using rubrics developed in an earlier phase of the project. These assessed the level at which students grasped the structure of the concept on a scale from 0 to 5 and proceeding from a non-causal response to a relational causal response. These scoring rubrics are further elaborated in Grotzer (2003).

After scoring for the number of each of the cognitive and/or metacognitive categories (described above) that the student used in their writing samples and post-unit interview, a Total Metacognitive Score was arrived at by adding up the instances of individual metacognitive category use for each student. This score was compared to posttest scores and the overall gain scores on the science unit assessments and students' ability to transfer the underlying relational causal model from density to pressure. The data was further dissected to compare the scores for each individual metacognitive category to posttest scores on the unit assessments to see if some categories correlated to a higher extent than others with the science assessment outcomes.

Outcomes and Discussion

Our analysis suggests a strong correlation between the number of metacognitive comments students made during their interviews and higher science assessment posttest scores. Students who made more metacognitive statements were also more likely to offer relational causal responses on their posttests, reflecting an ability to incorporate complex causal concepts to a greater extent. They were also more likely to transfer their understandings from density to the context of the pressure unit.

Students in all classes showed significant gains on the pre- and post-assessments (t (17) = −7.56, p < .0001), explaining 49% of the variance in scores suggesting that the curriculum was effective in helping students learn the density and pressure concepts embedded in difficult causal concepts. This was expected based upon previous research (e.g., Basca and Grotzer 2001; Houghton et al. 2000). Students who made greater numbers of metacognitive statements also had higher density post-scores. The total number of metacognitive statements on the post-interview for density was a significant predictor of density posttest score (F (1,18) = −11.41, p < .0001), accounting for 34% of the variance. Entering density pretest scores and metacognitive statements on the density post-interview into a multiple regression analysis, together they explain 63% of the variance in scores. Both were significant predictors (F (1, 18) = 12.19, p = .0033) and (F (2, 18) = 6.03, p = .0268) for density pretest score and metacognitive statements on the density post-interview (Total Metacognitive Score for Density), respectively. Figure 5.1 details the parameter estimates.

Students improved significantly in their ability to detect the underlying relational causality from pre- to posttest (t (17) = −4.97, p < .0001), with means of .67 (SD = .59) and 1.55 (SD = .70), respectively. Metacognitive score on density was a significant predictor (F (1, 18) = 5.03, p = .04) of students' ability to detect relational causal models on their posttest, explaining 24% of the variance (Density Relational Model Score = 0.49 + 0.11 × Total Metacognitive Density Score). Interestingly, pretest scores were not a significant predictor of posttest scores (F (1, 18) = 1.92, p = .18), explaining little of the variance (R^2 = .10).

Next, whether metacognition played a role in the transfer of learning gains in density to pressure was examined. Transfer was defined as detecting at least one relational model on a density posttest to reveal that they learned the base concept and then showing understanding of at least two of the possible three relational models on the pressure posttest to show that transfer to the target. A regression analysis revealed density posttest score to be a significant predictor of pressure posttest scores

$$\text{Intercept} = -0.67 + \left\{ + 1.07 \times \text{Density Pretest Score} \right\} \left\{ + 1.24 \times \text{Metacognitive Score on Density} \right.$$

Fig. 5.1 Prediction formula detailing parameter estimates (density pretest scores and metacognitive scores) to estimate density posttest scores

(F (1, 17) = 6.10, p = .03), explaining 29% of the variance. Of the 18 students in the subset, all but two had at least one relational model on the density posttest. Of these, only one student did not show a relational model on the pressure posttest. Metacognitive performance on the density post-interview was a significant predictor of whether or not students transferred the models as defined above (F (1, 15) = 4.73, p = .05), explaining 27% of the variance (Transfer Score = 0.23 + 0.06 × Total Metacognitive Density Score).

Students employed a diverse range of metacognitive strategies. In interviews, the most frequently used strategy was category B, explicit knowledge claim plus abstract reasoning to think through a particular idea. Higher scores of category B correlated to overall posttest scores (r = .25, p = .03). Yet, during classroom discussions, category D, exploring the limits of students' ideas using all three levels of metacognition (intelligibility, plausibility, and wide-applicability), surfaced the most frequently in both classrooms. Of the total metacognitive strategies used in both classes, category D was used 42.0% of the time, while category B was used 28.4% of the time, and category C was used 29.6% of the time.

The following category D statement shows a typical pattern in students' thinking, that is, the recognition of changes over time in his or her thinking. For example, when asked, "What's going on when density changes?" a student replied, "Well, I thought at first that it was kind of like a chemical change. It can be changed chemically, I think, but a physical change can also be done like compacting bread or pouring something in [to make it a mixed density] (Subject #112)." After doing the experiment, the student noticed how her thinking changed, and she was able to recognize the emergence of her new understanding.

At the end of the pressure interviews, students were asked to note any metacognitive strategies that were particularly useful to them. Students' responses indicated that comparing their ideas with other students' ideas and making connections to other areas of their learning were the most useful. The results of this self-assessment were consistent with the outcome of the interviews. Students with higher scores on these two strategies (intelligibility + wide-applicability) had higher overall gain scores (r = .27, p = .03). This supports the notion that students learn effectively by comparing their ideas to other students' ideas. It also supports the claim that connecting new ideas to familiar contexts helps students understand learning objectives. For example, at the end of a pressure interview, a student said:

> I remember how we were doing the balloon over the flask we did it in two different ways, getting the balloon in and getting the balloon out and that helped because you have to reverse your thinking and think about it in different ways. The more experiments you do, it's easier to connect things like concepts. And it's easier to believe it, once you see it. I think I'm more of a visual learner. If I see it, I can believe it more and comprehend it better. And I guess that helped a lot because a lot of times in science you can't explain a lot of things because they're just too hard. And you can't, like, visually show them. It's easier when you have an experiment and you have to reflect on it too. Like, what you understand about it and what you don't 'cuz it helps you to get a better understanding and learn more. And the practical application, like how we had to answer those questions about..., like, why are runways longer in Denver and San Francisco? It made you practically think about it. So it's not just like some topic you learn in school because you can like really apply it to the world. And, like, the airplanes, I never really realized how the difference in pressure above the wing and below the wing gave it like the plane lift. I never really thought of it that way. But now I can apply it and realize that's how the plane works and it makes more sense too because it's connected to something.

She reveals a sophisticated understanding of what's useful to her in her own learning and the importance of connection-making.

Which, if any, of these metacognitive strategies appeared to help students transfer their causal understanding between topics? There were many examples where students who made more metacognitive statements in the course of their interviews were also more likely to map the relevant analogical relationships when transferring concepts. In each case, they needed to detect the relationship of balance or imbalance between two things and figure out how to map it appropriately. This mapping did not always happen quickly and easily. Often students talked through how two concepts, for instance, how liquid gets pushed up a straw and why balloons get pushed out of car windows, mapped on to each other, considering and rejecting mappings that did not work along the way. Often multiple metacognitive strategies were utilized simultaneously, making connections as evidence to make sense of an idea, rather than purely abstract connection-making. For example, when thinking about what happens when drinking from a straw, one student compared independent and dependent clauses in English and their interdependence to how a straw works and how the two pressures (higher and lower) need to work together for an effect. The student actively reflected on what she had already learned about relational causality in a previous unit. She uses the third metacognitive tool "wide-applicability" to think about relational causality in a context that makes sense to her.

While individual metacognitive scores showed a clear relationship to greater transfer, interestingly, class metacognitive scores did not predict whether students transferred the models or not (F (1, 15) = .38, p = .54), explaining almost none of the variance in scores. However, there were clear instances where students appeared to influence one another and a culture of metacognition clearly emerged. The following exchange ensued in a classroom where the teacher explicitly facilitated a conversation about how relational causality helped students in revising their models of how a straw worked before and after an experiment designed to help them.

Student 1: I might have subconsciously made the connection. I knew what was happening—like, I knew one thing would affect the other, but I didn't go the extra step to put two and two together to get that it's relational causality.... I would say it [relational causality] did really help because I understood what was going on and how one could change the other. By throwing in relational causality it would kind of change what I was thinking about originally. Like, I guess I thought it was more or less a "Domino thing," that one thing would make the next happen in a chain, like that. But if you think about it as a relational causality, then you would have to change your idea from one thing causing the next to happen, then they keep on causing the next thing to happen … to that both go together to make one thing happen. Like, as you lessen the air pressure in the straw, the greater air pressure outside can force down, that makes the liquid able to rise up the straw. One thing starts the next.

Teacher: So can you say how you're thinking about it now?

Student 1: Well, like if both affect each other, then it's because that the air pressure in the straw lessening and the air pressure outside staying the same, the lesser air pressure inside and the greater air pressure outside causes the liquid to go up the straw.

Student 2: I don't think it's really like domino causality because we saw the two causes are high air pressure outside and no air pressure inside, but we already saw that with Mary's straw, there wasn't any air pressure. And she took out the air pressure from the inside the air pressure, but it didn't cause it to go up right away. It needs the other….

Student 3: Originally, I knew pressure was involved, but I never really thought of it as a relationship between high and low pressure. And to get the pressure itself is another relationship between force and area. And you can break it down and see how it works.

This conversation of this class illustrates a culture of reflective thinking. In this example, the students used all three metacognitive moves—intelligibility, wide-applicability, and plausibility. All three students interviewed from this class, despite different achievement levels, had two relational models on the density posttests (out of two possible relational questions). All three interviewees also had at least two relational models on the pressure posttest (out of three possible relational questions). Thus, all three interviewed students from this particular class met the criteria of how we defined transfer for this study. Anderson and Nashon (2006) found that the metacognitive dimensions or profile of metacognitive moves that individuals within groups employ may impact the learning of the group. A study that looks at these individual patterns and how they impact learning might address the lack of relationship between class metacognitive scores and transfer found here.

Summary

The results underscore the importance of metacognition in helping students to evaluate how they are structuring their ideas and to adopt more complex explanatory structures. Students who reflected upon and evaluated the structure of their models were more likely to realize the need to structure the concepts differently. In the classroom discussions, a clear shift in students from viewing learning as a process of transmission and the passive role that they assume in that context to viewing learning as a process of active construction where they need to own the sense-making process took place (Gunstone 1991). The early videotapes reveal that at the outset of the study, student dropped their books on the desks and prepared to listen and take notes. Many appeared surprised when they were asked to consider the intelligibility and plausibility of the ideas being presented and initially hung back and waited. In the coming weeks, they increasingly engaged in the metacognitive moves and became much more active participants in their learning.

Students who considered the plausibility of their ideas through the negotiation of whether or not their own notions of causality made sense to them were able to gain a deeper understanding of the particular causal form. This in turn supported their ability to apply the structure flexibly to new concepts. While the findings are correlational, students who engaged in metacognitive activities were more likely to transfer their understanding of causal structures between topics than those students who were not engaged in metacognitive activities. Students' preference for category C, intelligibility and wide-applicability, underscores the importance of connecting new ideas to familiar contexts and to helping students learn by comparing their ideas to other students' models. This type of comparison is a part of many modeling approaches where students try out various models and evaluate them in comparison to other models and which most effectively explains the evidence.

The above exploration underscores the promise of metacognition when there is deep structural knowledge to be learned and transferred (Zohar 1994). By encouraging deeper processing and giving students ownership for their sense-making, students are more likely to understand the logical structures, causal relationships, and mechanisms involved in the particular science content (Chin and Brown 2000; Zohar 1994). Given students' tendency toward default patterns, metacognition invites students to realize, reflect upon, and perhaps ultimately revise the underlying causal structures that they assign to particular concepts. This ultimately should enable them to develop a broader repertoire of causal concepts and also a reflective awareness about where they may apply. In turn, this should encourage deeper understanding in science and a greater likelihood that students will be able to deal with complexity in their lives.

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Appendix 1: Example of Materials-Based Metacognitive Activity in Density

Reflecting on What You've Learned About Changes in Density

In the past few classes, we have considered what causes differences in density at the microscopic level and how density can change. In your journal, please answer the following questions:

1. Of what you've learned about what causes differences in density, what makes sense to you? Are there any pieces of what you've learned that seem especially clear to you? What about it makes it easy to understand?
2. Of what you've learned about what causes differences in density, what doesn't make sense to you? What pieces seem especially difficult to understand? What about them makes them difficult?
3. Sometimes even when we understand an idea, we may not believe it. Comprehending an idea is not the same thing as believing it to be true. In terms of density, is there anything that you believe to be true? Why do you believe it to be true?
4. Is there anything that you believe is not true? Why do you believe it is not true?
5. Is there anything about what you learned about density that relates to other ideas you may have learned about? What are they? In what ways do they relate?

Appendix 2: Example of Teacher-Supported Metacognitive Activity in Density

Reflecting on Our Thinking as a Group

The more we can begin to understand our own thinking, the better we understand and process ideas in science. As an exercise to help us reflect on our thinking as individuals and as a group, we will watch a video from yesterday's lesson. As you watch the video, look for ways in which you use each other to make sense of ideas, to consider the plausibility of ideas, and to connect ideas to other areas of learning. Here is a list of possible situations to look for:

Instances where...

- When talking about his or her model, a student explains what makes sense to him/her. The student may explain why certain pieces are particularly clear and easy for him/her to understand. He or she may also talk about things that still seem unclear about an idea.
- After one student shares his/her response, other students understand the original student's model, they may understand parts of the model, or they may not understand the model at all.
- Students discuss their different understandings. After one student shares his or her model, other students in the class add to the first student's model to have the idea make sense to them.
- Students talk about whether or not they believe a particular model. Sometimes even if a model makes sense, you may not necessarily believe it. Can you recognize any examples when a student (or a group of students) talks about "getting" a particular model but not necessarily "buying" it? In other words, instances when students debate whether or not an idea is true?
- In the discussions, were there any instances when students referred to common experiences that you, as a class, have shared (or maybe not shared) that made thinking about this idea difficult to understand?
- Were there any common experiences or understandings that the class shares that helped class members make connections about this idea to other areas of learning? Was there any common theme that students tended to refer to when explaining their ideas?

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