Journal of Science Education and Technology, Vol. 13, No. 1, March 2004 (© 2004)

Fostering Students' Epistemologies of Models via Authentic Model-Based Tasks

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A curriculum unit for middle school Earth Science called "What's on Your Plate?" was designed. The unit was implemented in several middle and high school classrooms in California and Massachusetts. In the first implementation, the total number of students who participated was 1100. The unit was designed with two main pedagogical principles: make thinking visible, and help students learn from one another; both were derived from an inquiry-based framework. With these two main pedagogical principles as a larger guiding framework, we designed the curriculum to provide students with rich, iterative model-based activities for students to both learn with and provide criteria for them to critique their peers' work from the opposite coast. The goal here was to influence students' understanding of the domain as well as their understanding of the nature of models in science by engaging them in an authentic context in which they constructed and reasoned with models, as well as critiqued the models of their peers. Data from 15 classrooms is described both in terms of the gains students made of their understanding of the nature of models as measured by pencil and paper survey administered both before and after the unit. In addition, a small subset of students' data is shown to illustrate advances in students' understanding of models. Lastly, we show how students with more sophisticated epistemologies of models are better able to further their content understanding as compared to students with less sophisticated epistemologies of models.

KEY WORDS: model-based learning; learning with technology; collaborative learning; learning in plate tectonics.

INTRODUCTION

Current reform efforts seek to improve science understanding of our citizens as a whole by promoting lifelong learning such that knowledge can be integrated across topics in school and applied to real-world problems (Linn, 1999), such as understanding scientific findings described by the media. Being scientifically literate includes understanding science content, having scientific process and inquiry skills, and understanding the nature of science, i.e., what is taken as evidence (Perkins, 1986). Thus, in order to address scientific literacy effectively, we need to take into account the factors influencing each of these three aspects of science learning. Specifically, to address understanding of *content knowledge*, we need to take into account the repertoire of models students bring to instruction (Inhelder and Piaget, 1958; Linn *et al.*, 1994); to address *process and inquiry skills*, we need to design rich tasks that engage the learners in meaningful ways (Linn, 1999); and, to address *epistemic understanding*, we need to address students' (naive) views about the nature of science (Carey and Smith, 1995; Grosslight *et al.*, 1991; Smith *et al.*, 1999).

More recently, it has been argued that an important part of epistemic understanding also includes students' epistemologies of the nature and purpose of scientific models. Here we argue that the degree to which models can serve as usable representations of scientific phenomena depends on students' ability to understand models as abstracted representations

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1059-0145/04/0400-0007/0

of scientific phenomena, i.e., students' epistemological understanding of the nature of scientific models and their purpose as an explanatory framework of the scientific phenomena under inquiry (Gobert and Discenna, 1997; Schwarz and White, 1999). We also argue that epistemology is an important learner characteristic and as such is crucial to both unpacking how students learn from models (Gobert, 2003) and how to better design model-based learning materials.

The widespread use of technology in schools can provide great potential for impacting science instruction and science literacy (Linn, 1999), particularly if the design of our learning environments and activities engaged therein are guided by pedagogical principles informed by educational research. Despite technology's ubiquitous and ever increasing use in all levels of education, its potential offerings for science understanding, and the recognized importance of embedding technology within the science curricula (Linn *et al.*, 1994), there are a plethora of issues, both theoretical and applied, which are unaddressed in research to date. Two of these key issues that are addressed in this paper are: How can we use the technology effectively to promote deep learning in line with epistemic goals? and How can we identify change in students' epistemic understanding?

Theoretical Background

The proposed work draws upon varied literature bases from Cognitive Psychology and Science Education, namely, *causal models* (White, 1993; Raghavan and Glaser, 1995), *model-based reasoning* (Gilbert, 1991; Gobert, 2000), *model generation and comprehension* (Gobert, 1994; Gobert and Frederiksen, 1988; Kindfield, 1993; Larkin and Simon, 1987), text comprehension (van Dijk and Kintsch, 1983), *explanation and self-explanation* (Chi *et al.*, 1994; Coleman, 1995; Gobert, 1997a), *computer-supported learning* (Linn and Hsi, 2000; Scardamalia *et al.*, 1989), *science inquiry projects* (Glaser, 1976; Champagne *et al.*, 1980; Driver *et al.*, 1985; Collins *et al.*, 1991; White and Frederiksen, 1998; Linn and Hsi, 2000), and *epistemology*, both in general (Schommer, 1990, 1993), and *epistemology of science* in particular (Smith and Wenk, 2003; Bell and Linn, 2002). The two theoretical frameworks most heavily relied on are model-based learning (Clement *et al.*, 1989; Gobert and Buckley, 2000) and students' epistemologies of science (cf. Carey and Smith, 1995). Each will be addressed in turn. We also include an overview of WISE (Web-based Inquiry Science Environment; Linn and Hsi, 2000), and its curricular design principles since the present curriculum was designed and implemented using WISE.

Model-Based Teaching and Learning

In model-based learning, it is assumed that learners construct mental models of phenomena in response to a particular learning task (assuming the task has engaged the learner) by integrating pieces of information about the structure, function/behavior, and causal mechanisms. Reasoning with a model may instantiate evaluation of the model, leading to its revision or elaboration. Model revision involves modifying parts of an existing model so that is better explains a given system. For a more thorough description of this learning framework, see Gobert and Buckley (2000). In the present research, it is assumed that students construct and revise mental models as a result of engaging in model-based tasks. It is also assumed that students have content-specific prior knowledge in the form of mental models of phenomena that they bring to bear on the tasks in which they are engaged (Gobert, 2000).

Epistemology and Science Learning

Currently research on students' epistemologies encompass a broad range of perspectives and its definition remains controversial (Schommer-Aikins, 2002). At one end, students' epistemologies are described as stable, unitary structures such as traits that have a development or stage-like progression (cf., Perry, 1970, Carey and Smith, 1995; Smith and Wenk, 2003). Schommer departed from the developmental, unitary trait viewpoint by describing epistemology as a set of four beliefs including the stability of knowledge, the structure of knowledge, the speed of knowledge acquisition, and the control of knowledge acquisition; these may mature at different rates and are domain-specific (cf. Schommer-Aikins, 2002). At the farthest end of this continuum is the notion that epistemologies are best described as a situated, highly contextualized set of resources that students bring to bear on science problems at hand (Hammer, 1994; Hammer and Elby, 2002).

Research studies on epistemology have addressed students' views of the nature of learning in general (Schommer, 1990, 1993; Hofer and Pintrich, 2002) and in specific domains including science (Linn *et al.*, 1991; Hammer, 1994, 1995; Carey and Smith, 1995). More targeted studies have shown that students' epistemologies can influence students' learning outcomes (Songer and Linn, 1991; Perkins *et al.*, 1993). Other studies have investigated the influence of science learning on views of science (Carey and Smith, 1993; Davis, 1998; Chen and Klahr, 1999); however, results here were not consistently positive (Burbules and Linn, 1991; El Khalick and Lederman, 2000). A third set of studies are those that promote inquiry intertwined with learning disciplinary science knowledge. Here, Songer's computer as lab partner (Songer, 1989) showed that students' views of science were altered alongside their content learning. Bell (1998) who engaged 25 classes of students in collaborative debate about and argumentation about a controversial science topic also found that students made epistemological gains as well as significant gains in content understanding. The present research falls into this last category; namely, that students' epistemologies evolve alongside students' content learning. In fact, we suggest that engaging students in authentic scientific inquiry is an excellent pedagogical approach for promoting students' content learning, inquiry skill development, and understanding of the nature of science and of scientific models.

Scaffolded Knowledge Integration: WISE and Its Pedagogical and Philosophical Principles

One learning environment which was designed to promote integration of science content, scientific inquiry skills, and epistemic knowledge is WISE[3] (Web-based Inquiry Science Environment) developed by Marcia Linn and her group at University of California at Berkeley. WISE is an integrated set of software tools coupled with a project-based framework for middle and high school science curriculum focused around Web resources (Linn and Hsi, 2000). WISE which is based on over 10 years of research on knowledge integration is informed by its precursor, KIE (Knowledge Integration Environment; Linn and Hsi, 2000), and has a suite of tools to engage students in many types of scientific inquiry, including prompted reflection, electronic discussions, evidence sorting and argument mapping, collaborative search for evidence, collaborative design, and analysis and reporting (Linn, 1998). The four basic pedagogical principles for scaffolded knowledge integration embedded in WISE are: make science accessible for all students; make thinking visible; provide social support so that students can learn from each other; and promote autonomy and lifelong learning (Linn and Hsi, 2000).

Domain Studied

This domain was chosen for two reasons. First, it is an excellent domain in which to investigate students' model building because of the important role that model building and causal reasoning play in understanding the hidden mechanisms, e.g., convection underlying continental drift, earthquakes, volcanoes, mountain formation, and sea floor spreading. Briefly, the theory of plate tectonics states that the outer layer of the earth (the crust) is broken up into slabs (the plates) which move on the partially molten layer of the earth (the mantle) due to the convective movement of hot magma in the mantle (Feather *et al.*, 1995; Plummer and McGeary, 1996). Additionally, it is an excellent context in which to study students' epistemologies of models both because there are many excellent models with which to engage learners in model-based tasks, and theory of plate tectonics is a good example of the dynamic nature of science, how scientific inquiry proceeds, and how a hypothesis can be proposed, discarded, modified, and then redefined, as it was in the case of Wegner's original theory of plate tectonics (Le Grand, 1991).[4]

Relevant Background to Present Research

Fostering Students' Learning via Modeling and Interaction of Epistemology With Modeling

The proposed research draws on previous findings on modeling in continental drift and plate tectonics with middle school students. Briefly, studies conducted to date have addressed: the effects of a multimedia environment, CSILE (Scardamalia and Bereiter, 1992), on students' graphical and causal explanations of continental drift (Gobert *et al.*, 1993);

[3]For more information, see http://wise.berkeley.edu/WISE/index.html

[4]The theory of plate tectonics has changed our entire concept of earth dynamics in the past 35–40 years; earlier the idea of continental drift rated little more than a footnote in most introductory geology textbooks. As such, the theory of plate tectonics represents a major revolution in earth science (Plummer and McGeary, 1996) because it combines hypotheses about continental drift and sea floor spreading in order to provide a unified explanation of the past, present, and future geographic distribution of the earth's landmasses and oceans (Bencloski and Heyl, 1985).

the nature of students' preinstruction models of plate tectonics and learning difficulties encountered in this domain (Gobert, 2000); causal reasoning associated with models of varying levels of integration and the visual/spatial inferences afforded on the basis of models (Gobert, 2000); the benefits of student-generated diagrams versus summaries (Gobert and Clement, 1994, 1999) and student-generated diagrams versus explanations on content learning (Gobert, 1997a); the influence of students' epistemologies of models on learning in this domain (Gobert and Discenna, 1997); and the use of modeling and on-line collaboration as a means to promote understanding of content, inquiry skills, and epistemic understanding (Gobert *et al.*, 2001; Slotta *et al.*, 2001; Gobert *et al.*, 2002a,b).

Research on Students' Epistemology of Models and Its Relationship to Content Learning

Since learning in the domain of plate tectonics involves understanding and reasoning with models, a previous pilot study was conducted in order to address whether one's epistemology of scientific models influences the characteristics of the models students construct, and the inferences which are made on the basis of these models (Gobert and Discenna, 1997). The underlying hypothesis here was that students with a better understanding of the nature of scientific models would be better able to construct models and use these to make inferences about plate-tectonic-related phenomena. No significant differences were found between those with a more (or less) sophisticated epistemology of scientific models for the understanding the spatial aspects of the domain ($F = 0.001$, $p = 0.98$; $\text{mean}_{\text{naive epist}} = 6.0$, $\text{mean}_{\text{sophisticated epist}} = 6.3$) or for the understanding of causal/dynamic aspects of the domain ($F = 0.075$, $p = 0.79$; $\text{mean}_{\text{naive epist}} = 11.9$, $\text{mean}_{\text{sophisticated epist}} = 12.7$). However, those with a more sophisticated epistemology of the nature of models were better able to make inferences about other causal mechanisms involved in plate tectonics, e.g., convection as compared to their epistemologically less-sophisticated counterparts ($F = 4.7$, $p = 0.045$; $\text{mean}_{\text{naive epist}} = 2.4$, $\text{mean}_{\text{sophisticated epist}} = 5.7$) (Gobert and Discenna, 1997); that is, those who held more sophisticated epistemologies of science were better able to transfer what they had learned in order to answer more difficult conceptual items involving in the causal mechanisms of plate tectonics. Questions used to assess this were (a) explain why and how earthquakes are formed; (b) explain what convection zones are and where they occur; and (c) explain the difference between volcanic eruption caused by plates moving apart and volcanoes which are caused by the collision of an oceanic plate and a continental plate. These findings are consistent with studies of the effects of epistemology on integration of science information acquired from text (Rukavina, 1991; Rukavina and Daneman, 1996) and the effects of epistemology on integration of science concepts in general (Songer and Linn, 1991).

Present Research

The present work builds on and extends my existing research in order to design, test, and refine rich tasks for middle and high school students for learning in the domain of plate tectonics. The unit, "What's on your plate?" was designed using the relevant literature on learning in Earth Sciences, namely, misconceptions of plate tectonics of both the inside structure of the earth and of the causal mechanisms underlying plate-tectonic-related phenomena (Gobert and Clement, 1999; Gobert, 2000), and findings about students' knowledge integration difficulties in this domain (Gobert and Clement, 1994). The unit was also designed using two of the four WISE design principles (Linn and Hsi, 2000); namely Making Thinking Visible and Help Students Learning From One Another.

Make Thinking Visible

In the research presented, making thinking visible takes on a different meaning than that which was originally proposed by Collins *et al.* (1991). Here, we extend the notion of "making thinking visible" to utilize *visual modes* of representation in two ways: (1) engage students in drawing tasks to make their models explicit and use these as knowledge artifacts for both model revision as well as collaborative discourse, and (2) provide students with a set of *dynamic, runnable models* of plate tectonic phenomena. Here, students use the runnable prototypes to visualize dynamic, causal, and temporal processes in order to test, critique, and revise their own models. WISE prompts students to justify and explain their changes in order to reify learning. Prompts to be designed include "What does your new model include that it didn't before?", and "What does your new model describe or explain that it didn't before?"

Help Students Learn from One Another

In the research presented we sought to facilitate students' understanding of the nature of models by giving them model-based tasks such as those described above, as well as by giving them opportunities to think critically about their peers' models and write formal evaluations of them.

The Unit: "What's On Your Plate?"

The "What's on your plate?" unit the students in modeling activities (the topic of the present paper), in the following ways:

1. *Students' Model Building and Explanation of Their Models*. Students were asked to construct in WISE visual models of plate-tectonic-related phenomena; that is, each pair of students drew a model of how mountains are formed (East coast only) while students on the West coasts drew models of earthquake or volcanic eruption. Students were then asked to write in WISE a short explanation for their models with the following prompt "Now that you have drawn your model, write an explanation of what happens to each of the layers of the earth when an earthquake erupts (or a mountain is formed, a volcano erupts)." Once students had done these two steps, they posted their models and explanations for their learning partners on the opposite coast.
2. *Students' Evaluation and Critique of the Learning Partners' Models.* Students read two pieces of text in WISE called "What is a Scientific Model? And "How to evaluate a model?" in order to give them some basic knowledge with which to evaluate their leaning partners' models. Then students were prompted to critique learning partners' models using prompts that were presented in WISE. The prompts include
   1. Are the most important features in terms of what causes this geologic process depicted in this model?
   2. Would this model be useful to teach someone who had never studied this geologic process before?
   3. What important features are included in this model? Explain why you gave the model this rating.
   4. What do you think should be added to this model in order to make it better for someone who had never studied this geologic process before?

These prompts were designed to focus students' thinking about models in two general ways: causal mechanisms/processes depicted (Items 1 and 3), and the model as a communication tool to learn or reason with (Items 2 and 4). Prompts similar to the latter have been successful in getting students to generate rich explanations (Gobert, 1997b; in preparation), and it was believed that they might be successful here as well in getting students to think about how useful a model is as a tool for communication purposes. Once students discussed the evaluation with their in class partner (computer partner), they then posted their evaluation for their opposite coast learning partners to evaluate.

3. *Students' Model Revision and Justification*. Students read the evaluation that was written and posted by their learning partners on the opposite coast. They were the asked to revise their models based on the critique from their learning partners as well as the content knowledge they had learned from the unit (the model-based content activities will be discussed next). They were also asked to write a revised explanation for their new models. Lastly, here students were asked to justify their changes to their models in WISE in order to engage students in reflection about how their understanding had changed. Prompts here include

   > "I changed my original model of... because it did not explain or include...."
   >
   > "My model now includes or helps explain...."
   >
   > "My model is now more useful for someone to learn from because it now includes...."
   >
   > "I revised this on the basis of my learning partners' critique in the following ways...."
   > "I revised this on the basis of the activities in these WISE units...."

4. *Geology Websites*. As part of the unit students do an on-line field trip and are guided to visit multiple USGS websites with current data in order to the differences between the coasts in terms of their mountains, volcanoes, and earthquakes. After each "site visit," students write a relfection note for their learning partners on the oppoiste coast about what they have learned about earthquakes, volcanoes, and mountains on their coast. This reflection note is posted for the learning partners to read and relfect on in terms of how the

data observed differ from that of their own coast.

Students also visit a plate boundaries website in order to speculate about how the location, frequency, and magnitude of geological events (mountains, earthquakes, and volcanoes) "observed in Activity 2 are related to plate boundaries in the earth's crust. After visiting the plate boundaries website, students are asked to write a Reflection Note with the following prompt: Write one (or two) question(s) you have about plate boundaries or plate movement that will help you better understand why the geologic processes on the West and East coasts are different. Students revisit these questions in a Discussion Forum later in the unit.

5. *Dynamic-Runnable Models.* These models were designed in line with previous research which has shown that visualization facilitates the understanding of dynamic phenomena (Monaghan and Clement, 1995) and that middle and high school students can understand rich dynamic concepts if provided with the appropriate scaffolds and tools (Jackson *et al.*, 1994; Ploger and Della Vedova, 1999; Frederiksen, White, and Gutwill, 1999).

Students view and read about the different types of plate boundaries, namely, collisional, divergent, convergent, and transform boundaries in order to begin to think about how the location of and type of plate boundary are related to geological occurences on the earth's crust. Students reify their learning by writing reflection notes about what types of geological events are typical of specific types of plate boundaries.

Students also visit a model of mantle convection which is accompanied by a text which scaffolds their understanding of the dynamic and causal features of the model by directing their processing of the causal and dynamic information in the model as it "runs." Students write a reflection note to explain how processes inside the earth relate to plate movement.

Lastly, students visit a series of dynamic models which depict different types of plate convergence, namely, oceanic–oceanic convergence, oceanic–continental convergence, and continental–continental convergence. Again, students' understanding is scaffolded via a text which direts their processing of the causal and dynamic information in each model as it "runs."

Research Approach and Questions

In order to address our research question, we used a design study approach (Linn, 1999; Brown, 1992; diSessa, 1991). Design studies are used to investigate the impact of decisions about curricular materials with the express goal of redesigning them in accordance with the findings obtained (Linn, 1999).[5] We take the design study approach since this is the approach which works best with classrooms in which WISE is fully integrated into the science instruction. Our questions were: does model-building, learning with dynamic runnable visual models in WISE, and the process of critiquing peer's models promote a deeper understanding of the nature of models in science? and Is there a relationship between students' epistemologies of models and their content learning?

METHOD

Participants

Approximately 1100 students participated in the Spring 2001 implementation of "What's on your Plate?" These were drawn from 34 middle and high school classrooms across California and Massachusetts. From this large data set, data from 15 middle school classrooms was chosen for analysis in this paper. These data represent students from three different teachers (one in California and two in Massachusetts) each with five science classes. The total number of students upon which this subset is based is approximately 360. The students from one class on the West coast were partnered with the students from two classes on the East coast because of the differences in class sizes. Five such sets or "virtual classrooms" (referred to as WISE periods) were created in WISE.

Students were paired within their respective classes and then paired within their virtual WISE classes; thus, two students on the East coast were collaborating on line with two students on the West coast. Pairing students is typical in WISE classrooms as it stimulates discussion and deeper learning than students working alone (Linn and Hsi, 2000).

Procedure

Pretest and Posttest. Students were given pencil and paper survey to assess both their content

[5]Findings from the 2001 was used to revise the curriculum unit and the new unit was implemented again in Spring 2002.

knowledge of the plate tectonics (see Gobert *et al.*, 2002a for details; Gobert, submitted, and www.mtv.concord.org), and their understanding of the nature of models both before and after the unit; the same test was given before and after. The nature of models part of the test was adapted from Gobert and Discenna (1997), and includes the following questions:

> How would you describe what a model (in science) is to someone who didn't know this term. Give two examples of models.
>
> What are models in science used for?
>
> How close does a model have to be to the real thing?
>
> What is important to include in a scientific model?
>
> Can scientists have more than one model for the same thing? Explain your answer.
>
> Are there circumstances that would require a model to be changed? If yes, what are they? If no, why not?

These questions were each scored using a scheme ranging from 0 to 3 to reflect increasingly more sophisticated epistemologies respectively. Further information about the coding scheme can be seen in Gobert *et al.* (2002b) or Gobert and Discenna (1997).

RESULTS

The data analysis is described in three parts. The first part describes the increases made in students' understanding of the nature of models as measured by pre–post gains. The second part describes examples of pre–post gain in specific students. The third part describes an analysis which compared the postunit content knowledge of epistemologically sophisticated versus epistemologically naïve students.

Part 1

Analysis of Variance of WISE Periods 1–5. Analysis of variance was used on the total pre- and postscore on the models survey and computed for each WISE period (1–5). Again, since this is a design study, we are not comparing these to a "control" group, so the purpose of the analyis of variance is to get a general sense of whether the students' undersanding of the nature of models (as measured by the survey) had changed after the unit.

In all five WISE periods, we found a significant change from the pre- to the posttest; thus, it appears that the unit promoted epistemological change in the students. In each WISE period, collapsing over teacher, the effect is significant. See Appendices A1, A2, A3, A4, and A5 for the relevant ANOVA table, tables of means and standard deviations, and figures. See Table I for a summary of these findings.

Table I. Summary of Epistemological Gains for Each WISE Period

	F value	p value
WISE Period 1	16.046	$=.0002$
WISE Period 2	40.95	$<.0001$
WISE Period 3	54.80	$<.0001$
WISE Period 4	35.77	$<.0001$
WISE Period 5	75.51	$<.0001$

Part 2

In this section, examples of students' responses on the pre- and posttest data are given to show how students' understanding of models changed as a result of the model-based unit, "What's on your plate?." In the examples given, the scoring is in parentheses, e.g. (2) and the italicized parts show why it was coded as such.

> *Question 1: How would you describe what a model (in science) is to someone who didn't know this term?*

Subject S. W.

> Pre: "Cardboard box, slinky" (draws pictures of each) (1)
>
> Post: "A model visually shows something. One model could stand still, another could move." (draws pictures—2D earth with plain, plateau, lake, and a wave over land) the wave moves (2)

Subject K. F.

> Pre: no response (0)
>
> Post: "I would describe a model as a symbol for something in the real world or almost a visual dictionary for a process in science. A model in science could show making of volcanoes, like what we did in the WISE project or even the formation of a log into petrified wood." (3)
>
> *Question 2: What are models in science used for?*

Subject M. X.

> Pre: "They are used to explain information." (2 *ambiguous use of explain*)
>
> Post: "Showing people how and why things happen." (3)

Subject K. F.

Pre: "To show something that happens for science in a smaller area." (2 *ambiguous use of happens*)

Post: "Models in science are used for showing a process that happens in real life that is hard to make a copy of, such as formation of volcanoes." (3)

Question 3: How close does a model have to be to the real thing?

Subject J. B.

Pre: "A model has to almost be exact to be the real thing." (1)

Post: "A model has to be pretty close to the real thing if it's going to show something happening." (2)

Subject M. B.

Pre: "It could be anything that has something to do with your topic. If you had to do a model of a cat, you could do a poster with pictures." (0)

Post: "A model just has to show what it is or how it works, so it really depends on the project." (3)

Question 4: What is important to include in a scientific model?

Subject J. G.

Pre: "All the different parts of the model." (1)

Post: "An important thing to remember to include in a scientific model is a key, labels, or some kind of information that would help us to better understand it." (2)

Subject J. C.

Pre: "So you do not make a mistake on the real thing." (2)

Post: "The details and movement to prove things." (3)

Question 5: Can scientists have more than one model for the same thing?

Subject K. W.

Pre: "No, because for each thing you could include all the information in one model." (0)

Post: "Yes, because there can be more than 1 different way to solve the problem." (3)

Subject N. L.

Pre: no response (0)

Post: "Yes, they can because not all the scientists are going to have the same evidence and explanation on something." (3)

Question 6: Are there any circumstances that would require a model to be changed?

Subject J. C.

Pre: "Yes, if it has some glitch that is bad." (1)

Post: "If something is built wrong they have to change it or add variables." (3)

Subject A. M.

Pre: "Yes, because if something happens and the model shows the way it was before it changed then it would be wrong." (2)

Post: "Yes if more research proved the thing wrong." (3)

Part 3

After analyzing the pre–post gains of the students, we sought to investigate whether the students with a more sophisticated epistemology of the nature of models also scored higher on the postunit assessment of the content covered in the unit. In accordance with a previous pilot study (Gobert and Discenna, 1997), we hypothesized that those with a more sophisticated understanding of the nature of models might be able to drive their content understanding further than their epistemologically naïve counterparts. To address this, we selected from five randomly selected WISE periods ($n = 350$), the students who scored in the upper third on the epistemology of models survey as well as those who scored in the lower third on the epistemology of models survey. These students were grouped into two categories forming the independent variable, i.e., epistemologically sophisticated versus epistemologically naïve, respectively. Prior knowledge, as measured by the pretest (identical to the posttest) was used as a covariate, thereby holding constant any possible effects on the posttest due to prior knowledge. Analysis of variance was conducted using content knowledge as measured by the posttest as the dependent variable. Our hypothesis was confirmed; that is, those who were more epistemologically sophisticated scored significantly higher on the posttest than did their epistemologically naïve counterparts ($F = 4.10$, $p = 0.04$).[6] We interpret these findings to mean that those who had a more sophisticated understanding of the nature of

[6]It is also important to note that the interaction between epistemology level and prior knowledge was not statistically significant indication the covariate (prior knowledge) had a similar effect for both levels of epistemology.

models were better able to use this knowledge to impact their content learning as compared to their epistemologically less-sophisticated peers.

DISCUSSION

This research utilized a state of the art science learning environment, WISE (Linn and Hsi, 2000), to promote deep learning of subject-matter material in plate tectonics (Gobert *et al.*, 2002a) and to foster students' epistemological knowledge of the nature of scientific models. We effectively implemented the "What's on our plate?" curriculum into multiple classrooms. Results from the study suggest that students achieved a deeper understanding of the nature of models, as evidenced by significantly higher scores on the posttest; furthermore, we assume that this was due to their experiences with the unit.

Further data analysis is necessary in order to characterize students' reasoning with models as a possible index of how their understanding of models is used in situ. This is particularly important since there is currently debate as to whether students' epistemologies can be measured using a pencil and paper task (Hammer, 2001). Additional analysis of this data (which is stored on the WISE server) will provide insight into this, in particular if those who have a very sophisticated understanding of models are also able to better use this knowledge to reason with models, do model critiquing, etc. Regardless of whether one believes that views of science influence learning, that pedagogies influence views of science, or whether epistemologies and content learning coevolve, there is some consensus that in order to understand the relationship between epistemology and science learning more fully, we need to develop more fully our understanding of the construct of epistemology (Smith and Wenk, 2003; Hammer and Elby, 2002). The present work attempts to provide some insight into the nature of students' epistemologies in an authentic learning context.

In this program of research, we are also interested in characterizing how epistemologies impact content learning. Our results showed that epistemologically sophisticated students also made greater content gains as compared to their epistemologically less-sophisticated peers. We believe that students' epistemological knowledge is being harnessed or bootstrapped to support students' content learning; that is, if a student has a better understanding of the nature of models and how models are used to make predictions, etc., the students is likely to make use of this knowledge when learning from and reasoning with models. Further research is necessary in order to more fully characterize how epistemological bootstrapping supports the learning of content knowledge. Further research is also necessary to extract the possible effects due to general intelligence.

Summary

In many research programs to date, students are presented with models to learn with (Raghavan and Glaser, 1995; White and Frederiksen, 1990). A "second generation approach" has engaged students in tasks which require them to construct their own models for deep content learning (Gobert and Clement, 1994, 1999; Gobert, 2000; Penner *et al.*, 1997). The present research extends this vein of progressive model-building in science education (cf., Raghavan and Glaser, 1995; White and Frederiksen, 1990) by having students critique each other's models as a way to promote deep understanding of both content as well of the nature of models. Furthermore, our modeling tasks are scaffolded using a model-based scaffolding framework (Gobert, 2003) which supports learners. More specifically, we provide students with appropriate guidance in order to construct and revise their own models, and reify what they have learned by reflecting on what their revised models help them explain that their original one did not. We scaffold their knowledge acquisition from models which is important since all information is presented simultaneously. We also guide students to pose questions in order to move their understanding forward, reflect on their own understanding, evaluate and critique their peers' models, and lastly, provide opportunities for students to reify what they have learned and transfer it to other situations. We argue that engaging and supporting students in authentic model-based learning promotes both deep understanding of content knowledge (Gobert et al., 2002a) as well as deep understanding of models and how they are used in science. It is believed that curricula such as this one which is designed in line with students' prior knowledge and designed to support students' inquiry skills and epistemological development can significantly scientific literacy in the long run (Linn and Muilenberg, 1996).

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation REC-9980600 in the form of a

APPENDICES

Appendix A1: Statistics and Figure for Period 1 Epistemological Gains

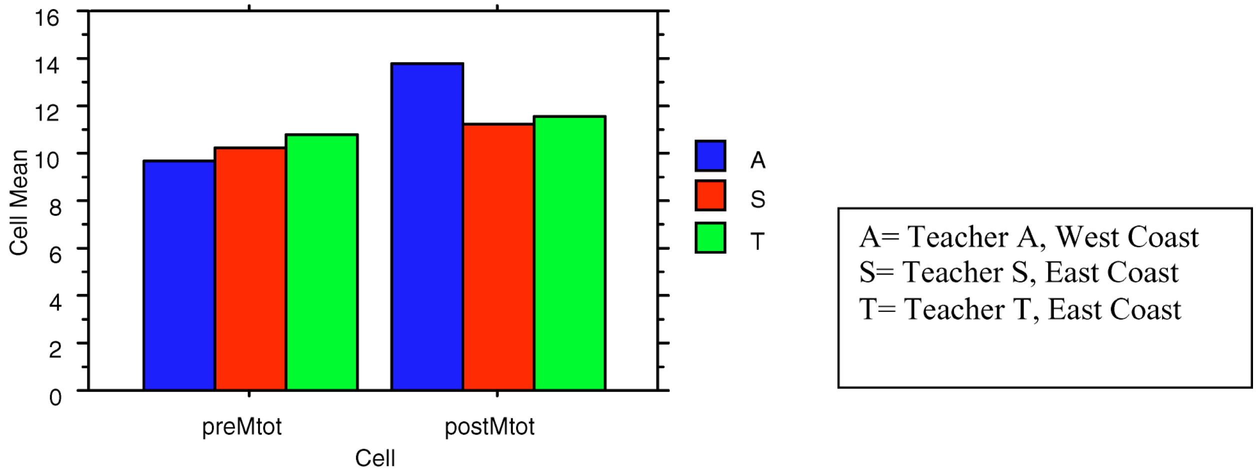
ANOVA Table for modelgain

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	22.442	11.221	.692	.5044	1.384	.157
Subject(Group)	61	988.926	16.212				
Category for modelgain	1	115.697	115.697	16.046	.0002	16.046	.987
Category for modelgain * teacher	2	83.882	41.941	5.817	.0049	11.633	.866
Category for modelgain * Subject(Group)	61	439.837	7.210				

Means Table for modelgain
Effect: Category for modelgain * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preMtot	29	9.672	4.386	.814
A, postMtot	29	13.793	2.392	.444
S, preMtot	17	10.235	2.835	.687
S, postMtot	17	11.206	2.616	.635
T, preMtot	18	10.833	3.068	.723
T, postMtot	18	11.611	4.418	1.041

Interaction Bar Plot for modelgain
Effect: Category for modelgain * teacher



Fisher's PLSD for modelgain
Effect: teacher
Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value
A, S	1.012	1.571	.2047
A, T	.511	1.543	.5139
S, T	-.502	1.739	.5692

Appendix A2: Statistics and Figure for Period 2 Epistemological Gains

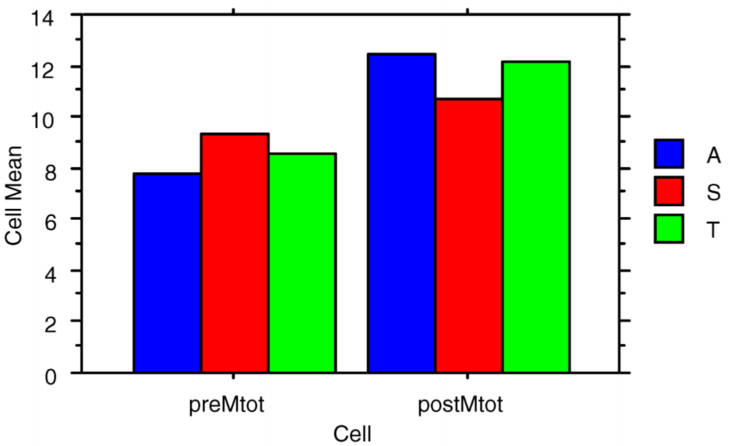
ANOVA Table for modelgain

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	2.335	1.167	.079	.9244	.158	.061
Subject(Group)	59	874.504	14.822				
Category for modelgain	1	311.401	311.401	40.945	<.0001	40.945	1.000
Category for modelgain * teacher	2	56.782	28.391	3.733	.0297	7.466	.659
Category for modelgain * Subject(Group)	59	448.710	7.605				

Means Table for modelgain
Effect: Category for modelgain * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preMtot	28	7.750	3.693	.698
A, postMtot	28	12.464	2.812	.531
S, preMtot	17	9.294	2.812	.682
S, postMtot	17	10.735	2.927	.710
T, preMtot	17	8.559	4.984	1.209
T, postMtot	17	12.176	2.243	.544

Interaction Bar Plot for modelgain
Effect: Category for modelgain * teacher



A= Teacher A, West Coast
S= Teacher S, East Coast
T= Teacher T, East Coast

Fisher's PLSD for modelgain
Effect: teacher
Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value
A, S	.064	1.632	.9380
A, T	-.289	1.632	.7268
S, T	-.353	1.827	.7028

Appendix A3: Statistics and Figure for Period 3 Epistemological Gains

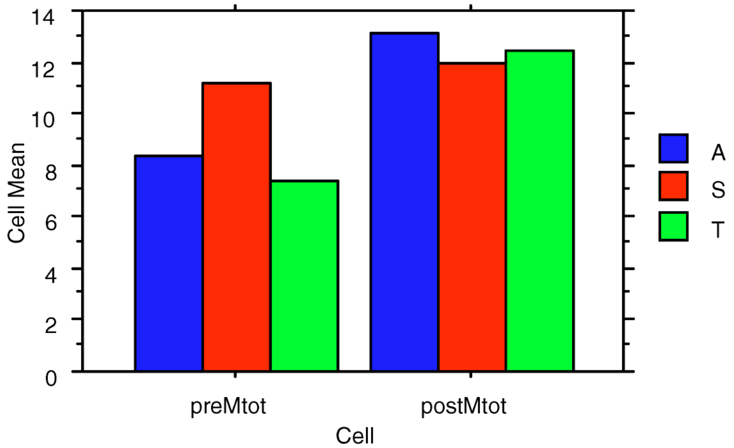
ANOVA Table for modelchange

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	47.195	23.597	1.433	.2464	2.866	.285
Subject(Group)	62	1021.132	16.470				
Category for modelchange	1	366.531	366.531	54.803	<.0001	54.803	1.000
Category for modelchange * teacher	2	106.362	53.181	7.952	.0008	15.903	.958
Category for modelchange * Subject(Group)	62	414.665	6.688				

Means Table for modelchange
Effect: Category for modelchange * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preMtot	30	8.400	3.885	.709
A, postMtot	30	13.100	2.896	.529
S, preMtot	17	11.206	2.469	.599
S, postMtot	17	11.912	1.314	.319
T, preMtot	18	7.417	5.168	1.218
T, postMtot	18	12.417	3.214	.758

Interaction Bar Plot for modelchange
Effect: Category for modelchange * teacher



A= Teacher A, West Coast
S= Teacher S, East Coast
T= Teacher T, East Coast

Fisher's PLSD for modelchange
Effect: teacher
Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value
A, S	-.809	1.684	.3437
A, T	.833	1.654	.3207
S, T	1.642	1.876	.0857

Appendix A4: Statistics and Figure for Period 4 Epistemological Gains

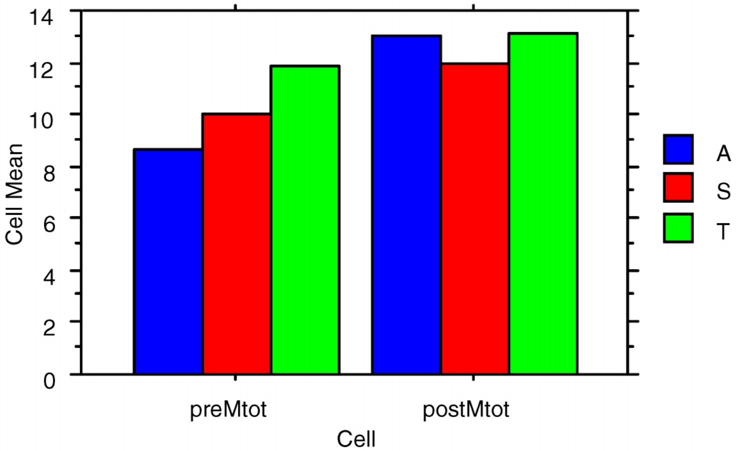
ANOVA Table for modelchange

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	63.678	31.839	2.807	.0681	5.614	.523
Subject(Group)	62	703.214	11.342				
Category for modelchange	1	190.437	190.437	35.768	<.0001	35.768	1.000
Category for modelchange * teacher	2	65.833	32.917	6.182	.0036	12.365	.889
Category for modelchange * Subject(Group)	62	330.098	5.324				

Means Table for modelchange
Effect: Category for modelchange * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preMtot	30	8.700	4.172	.762
A, postMtot	30	13.067	2.434	.444
S, preMtot	17	10.000	2.385	.578
S, postMtot	17	11.912	2.033	.493
T, preMtot	18	11.861	2.667	.629
T, postMtot	18	13.083	2.151	.507

Interaction Bar Plot for modelchange
Effect: Category for modelchange * teacher



A= Teacher A, West Coast
S= Teacher S, East Coast
T= Teacher T, East Coast

Fisher's PLSD for modelchange
Effect: teacher
Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value	
A, S	-.073	1.392	.9180	
A, T	-1.589	1.367	.0231	S
S, T	-1.516	1.551	.0552	

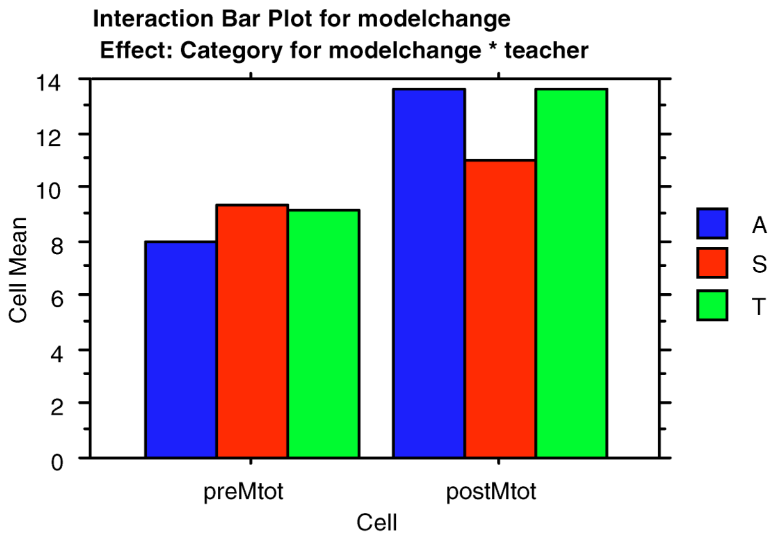
Appendix A5: Statistics and Figure for Period 5 Epistemological Gains

ANOVA Table for modelchange

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	26.202	13.101	.840	.4368	1.680	.181
Subject(Group)	60	936.016	15.600				
Category for modelchange	1	444.676	444.676	75.513	<.0001	75.513	1.000
Category for modelchange * teacher	2	90.227	45.113	7.661	.0011	15.322	.950
Category for modelchange * Subject(Group)	60	353.325	5.889				

Means Table for modelchange
Effect: Category for modelchange * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preMtot	29	8.017	4.133	.767
A, postMtot	29	13.621	3.305	.614
S, preMtot	19	9.289	3.194	.733
S, postMtot	19	10.947	2.248	.516
T, preMtot	15	9.133	3.691	.953
T, postMtot	15	13.567	1.689	.436



A= Teacher A, West Coast
S= Teacher S, East Coast
T= Teacher T, East Coast

Fisher's PLSD for modelchange
Effect: teacher
Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value
A, S	.701	1.631	.3970
A, T	-.531	1.758	.5510
S,T	-1.232	1.909	.2040

research grant made to The National Science Foundation. Any opinions, findings expressed are those of the authors and do not necessarily reflect the views of the National Science Foundation. This paper is based on an earlier paper presented at NARST, Gobert *et al.*, 2002b).

REFERENCES

Abd-El-Khalick, F., and Lederman, N. G. (2000). The influence of history of science courses on student's views of nature of science. *Journal of Research in Science Teaching* 37(10): 1057–1095.

Bell, P. (1998). *Designing for Students' Science Instruction Using Argumentation to Classroom Debate*, Unpublished Doctoral Dissertation, University of California at Berkeley, Berkeley, CA.

Bell, P., and Linn, M. C. (2002). Beliefs about science: How science instruction contribute? In Hofer, B., and Pintrich, P. (Eds.), *Personal Epistemology: The Psychology of Beliefs About Knowledge and Knowing*, Erlbaum, Hillsdale, NJ, pp. 103–118.

Bencloski, J. W., and Heyl, R. J. (1985). Teaching plate tectonics with the aid of a model of sea-floor dynamics. *Journal of Geological Education* 33: 274–276.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *Journal of the Learning Sciences* 2: 141–178.

Burbules, N. C., and Linn, M. C. (1991). Science education and the philosophy of science: Congruence or contradiction? *International Journal of Science Education* 13: 227–241.

Carey, S., and Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist* 28: 235–251.

Carey, S., and Smith, C. (1995). On understanding the nature of scientific knowledge. In Perkins, D., Schwartz, J., Maxwell West, M., and Stone Wiske, M. (Eds.), *Software Goes to School*, Oxford University Press, Oxford, UK.

Champagne, A. B., Klopfer, L. E., and Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. *American Journal of Physics* 48: 1074–1079.

Chen, Z., and Klahr, D. (1999). All other things being equal: Children's acquisition and transfer of the Control of Variables Strategy. *Child Development* 70: 1098–1120.

Chi, M. M. T., de Leuw, N., Chiu, M. H., and LaVancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science* 18: 439–478.

Clement, J., Brown, B., and Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding "anchoring conceptions" for grounding instruction on students' intuitions. *International Journal of Science Education* 11: 554–565.

Coleman, E. (1995). Learning by explaining: Fostering collaborative progressive discourse in science. In Beun, R. J., Baker, M. J., and Reiner, M. (Eds.), *Natural Dialogue and Interactive Student Modeling*, Springer, Berlin, Germany, pp. 123–135.

Collins, A., Brown, J. S., and Hollum, A. (1991). Cognitive apprenticeship: Making thinking visible. *American Educator* 6: 38–46.

Davis, E. A. (1998). *Scaffolding Students' Reflection for Science Learning*, Unpublished Doctoral Dissertation, University of California at Berkeley, Berkeley, CA.

diSessa, A. A. (1991). Local sciences: Viewing the design of human–computer systems as cognitive science. In Carroll, J. M. (Ed.), *Designing Interaction: Psychology at the Human–Computer Interface*, Cambridge University Press, Cambridge, England, pp. 162–202.

Driver, R., Guesne, E., and Tiberghien, A. (1985). *Children's Ideas in Science,* Open University Press, Philadelphia, PA.

Feather, R., Snyder, S., and Hesser, D. (1995). *Earth Science*, Glencoe/McGraw-Hill, Westerville, OH.

Frederiksen, J., White, B., and Gutwill, J. (1999). Dynamic mental models in learning science: The importance of constructing derivational linkages among models. *Journal of Research in Science Teaching* 36(7): 806–836.

Gilbert, S. (1991). Model building and a definition of science. *Journal of Research in Science Teaching* 28: 73–79.

Glaser, R. (1976). Cognitive psychology and instructional design. In Klahr, D. (Ed.),*Cognition and Instruction*, Erlbaum, Hillsdale, NJ, pp. 303–316.

Gobert, J. (1994). *Expertise in the Comprehension of Architectural Plans: Contribution of Representation and Domain Knowledge,* Unpublished Doctoral Dissertation, University of Toronto, Toronto, Ontario.

Gobert, J. (1997a). The effects of summarizing, explaining, and diagramming on text-base representations and mental models. *Presented at the Eighth Annual Winter Text Conference*, Jackson Hole, WY, January 18–24, 1997.

Gobert, J. (1997b). Summarizing, explaining, and diagramming: The differential effects on text-base representations and mental models. *Presented at the Nineteenth Annual Meeting of the Cognitive Science Society, Stanford University*, Palo Alto, CA, August 7–10, 1997.

Gobert, J. (2000). A typology of models for plate tectonics: Inferential power and barriers to understanding. *International Journal of Science Education* 22: 937–977.

Gobert, J. (2003). *Students' Collaborative Model-Building and Peer Critique On-line*. Presented at the National Association for Research in Science Teaching, Philadelphia, PA, March 23–26.

Gobert, J., and Buckley, B. (2000). Special issue editorial: Introduction to model-based teaching and learning. *International Journal of Science Education* 22: 891–894.

Gobert, J., and Clement, J. (1994). Promoting causal model construction in science through student-generated diagrams. *Presented at the Annual Meeting of the American Educational Research Association*, New Orleans, LA, April 4–8, 1994.

Gobert, J., and Clement, J. (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching* 36: 39–53.

Gobert, J., Coleman, E., Scardamalia, M., and Bereiter, C. (1993). Restructuring the classroom: Implementing knowledge-building via CSILE. *Presented at the Annual Meeting of the American Educational Research Association*, Atlanta, GA.

Gobert, J., and Discenna, J. (1997). *The Relationship Between Students' Epistemologies and Model-Based Reasoning* (ERIC Document Reproduction Service No. ED409164), Western Michigan University, Department of Science Studies, Kalamazoo, MI.

Gobert, J., and Frederiksen, C. (1988). The comprehension of architectural plans by expert and sub-expert architects. *Proceedings of the Tenth Annual Meeting of the Cognitive Science Society,* Montreal, Canada, Erlbaum, Hillsdale, NJ, pp. 651–657.

Gobert, J., Slotta, J., and Pallant, A. (2001). A WISE Inquiry Project for students' East-West Coast collaboration. *Submitted to the Annual Meeting of the American Educational Research Association*, New Orleans, LA, April 1–5, 2001.

Gobert, J., Slotta, J., Pallant, A., Nagy, S., and Targum, E. (2002a). A WISE Inquiry Project for students' East-West Coast collaboration. *Presented at the Annual Meeting of the American Educational Research Association*, New Orleans, LO, April 1–5, 2002.

Gobert, J., Snyder, J., and Houghton, C. (2002b). The influence of students' understanding of models on model-based reasoning. *Presented at the Annual Meeting of the American Educational Research Association*, New Orleans, LO, April 1–5, 2002.

Grosslight, L., Unger, C., Jay, E., and Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching* 28: 799–822.
Hammer, D. (1994). Epistemological beliefs in introductory physics. *Cognition and Instruction* 12: 151–183.
Hammer, D. (1995). Epistemological considerations in teaching introductory physics. *Science Education* 79: 393–413.
Hammer, D. (2001, July). Informal Discussion at CILT Epistemology Workshop, Concord, MA, The Concord Consortium.
Hammer, D., and Elby, A. (2002). On the form of a personal epistemology. In Hofer, B., and Pintrich, P. (Eds.), *Personal Epistemology: The Psychology of Beliefs About Knowledge and Knowing,* Erlbaum, Hillsdale, NJ.
Hofer, B., and Pintrich, P. (2002). *Personal Epistemology: The Psychology of Beliefs About Knowledge and Knowing*, Erlbaum, Hillsdale, NJ.
Inhelder, B., and Piaget, J. (1958). *The Growth of Logical Thinking From Childhood to Adolescence*, Basic Books, New York.
Jackson, S., Stratford, S., Krajcik, J., and Soloway, E. (1994). Making dynamic modeling accessible to pre-college science students. *Interactive Learning Environments* 4: 233–257.
Kindfield, A. A. C. (1993). Biology diagrams: Tools to think with. *Journal of the Learning Sciences* 3: 1–36.
Larkin, J., and Simon, H. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science* 11: 65–100.
Le Grand, H. E. (1991). *Drifting Continents and Shifting Theories*, Cambridge University Press, Cambridge, UK.
Linn, M. C. (1998). *Supporting Teachers and Encouraging Lifelong Learning: A Web-Based Integrated Science Environment (WISE),* Proposal funded by the National Science Foundation.
Linn, M. C., diSessa, A., Pea, R. D., and Songer, N. B. (1994). Can research on science learning and instruction inform standards for science education? *Journal of Science Education and Technology* 3: 7–15.
Linn, M. C., and Hsi, S. (2000). *Computers, Teachers, Peers: Science Learning Partners*, Erlbaum, Hillsdale, NJ.
Linn, M. C., and Muilenberg, L. (1996). Creating lifelong science learners: What models form a firm foundation? *Educational Researcher* 25: 18–24.
Linn, M. C., Songer, N. B., and Lewis, E. L. (1991). Overview: Students' models and epistemologies of science. *Journal of Research in Science Teaching* 28: 729–732.
Monaghan, J. M., and Clement, J. (1999). Use of a computer simulation to devlop mental simulations for learning relative motion concepts. *International Journal of Science Education* 21(9): 921–944.
Penner, D. E., Giles, N. D., Lehrer, R., and Schauble, L. (1997). Building functional models: designing an elbow. *Journal of Research in Science Teaching*, 34(2):125–143.
Perkins, D. (1986). *Knowledge as Design*, Erlbaum, Hillsdale, NJ.
Perry, W. G. (1970). *Forms of Intellectual and Ethical Development in the College Years: A Scheme*. Holt, Rinehart and Winston, New York.
Perkins, D. N., Jay, E., and Tishman, S. (1993). Beyond abilities: A dispositional theory of thinking. *Merrill-Palmer Quarterly* 39: 1–21.
Ploger, D., and Della Vedova, T. (1999). Dynamic charts in the elementary classroom. *Learning and Leading With Technology* 26: 38–41.
Plummer, C., and McGeary, D. (1996). *Physical Geology*, Wm. C. Brown Publishers, Dubuque, IA.
Raghavan, K., and Glaser, R. (1995). Model-based analysis and reasoning in science: The MARS curriculum. *Science Education* 79: 37–61.
Rukavina, I. (1991). *The Effect of Knowledge-Building Approach on Advancing Learning in Science*, Unpublished Doctoral Dissertation, University of Toronto, Toronto, Ontario.
Rukavina, I., and Daneman, M. (1996). Integration and its effects on acquiring knowledge about competing scientific theories from text. *Journal of Educational Psychology* 88: 272–287.
Scardamalia, M., McLean, R. S., Swallow, J., and Woodruff, E. (1989). Computer-supported intentional learning environments. *Journal of Educational Computing Research* 5(1): 51–68.
Schommer, M. (1990). Effects of beliefs about the nature of knowledge on comprehension. *Journal of Educational Psychology* 82: 498–504.
Schommer, M. (1993). Epistemological development and academic performance among secondary students. *Journal of Educational Psychology* 85: 406–411.
Schommer-Aikins, M. (2002). An evolving theoretical framework for an epistemological belief system. In Hofer, B., and Pintrich, P. (Eds.), *Personal Epistemology: The Psychology of Beliefs About Knowledge and Knowing*, Erlbaum, Hillsdale, NJ.
Schwarz, C., and White, B. (1999). What do seventh grade students understand about scientific modeling from a model-oriented physics curriculum? *Presented at the National Association for Research in Science Teaching*, Boston, MA, March 28–31, 1999.
Slotta, J., Linn, M. C., Gobert, J., and Pallant, A. (2001). Collaborative design of WISE Collaborative Inquiry Curriculum: A case study.*Submitted to Computer Supported Collaborative Learning*, Boulder, CO, January 2001.
Smith, C., Maclin, D., Houghton, C., and Hennessy, M. G. (1999). Can 6th-grade students develop a coherent constructivist epistemology of science: A comparative study. *Presented at the National Association for Research in Science Teaching*, Boston, MA, March 28–31, 1999.
Smith, C., and Wenk, L. (2003). The relation among three aspects of College Freshman's epistemology of science. *Presented at the National Association for Research in Science Teaching*, Philadelphia, PA, March 26, 2003.
Songer, N. B. (1989). *Promoting integration of instructed and natural world knowledge in thermodynamics*. Unpublished Doctoral Dissertation. University of California, Berkeley.
Songer, N. B., and Linn, M. C. (1991). How do students' views of science influence knowledge integration? *Journal of Research in Science Teaching* 28: 761–784.
Van Dijk, T., and Kintsch, W. (1983). *Strategies of Discourse Comprehension.* New York: Academic Press.
White, B. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction* 10: 1–100.
White, B., and Frederiksen, J. (1990). Causal model progressions as a foundation for intelligent learning environments. *Artificial Intelligence* 24: 99–157.
White, B. Y., and Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction* 16(1): 3–118.