The effects of different learning tasks on model-building in Plate Tectonics: diagramming versus explaining.

Janice D. Gobert

The Concord Consortium

10 Concord Crossing, Suite 300

Concord MA 01742

jgobert@conord.org

Ph: (978) 318.6975

Fax: (978) 371.3354

Abstract

Geology is a complex, semantically rich domain involving the interpretation of geological maps as external visualizations. Geological maps are complex in particular because 3-dimensional features must be inferred from 2-dimensional representations depicted by differing line types and weights. Modeling building, as an internal mental activity, is also required in order to achieve deep understanding of textual materials in geology, of geological maps, as well as in understanding complex causal processes, e.g., convection, underlying geological phenomena. Using literature from Cognitive Psychology, a framework for teaching and learning with visualizations in Plate Tectonics is given as an example of one difficult topic in Geology which involves the understanding of visualizations. Based on previous work in students' conceptions in Geology, three studies of students' conceptions and cognition in plate tectonics were designed. These studies highlight the importance of progressive model-building as a good pedagogical approach, as well as examine the efficacy of different learning tasks as strategies to promote model-building on the part of learners.

Keywords: learning with diagrams, model-building, learning in Plate Tectonics

Introduction

Geology is a complex domain which requires interpreting and reasoning with visualizations that are semantically-rich (Frederiksen & Breuleux, 1988). More specifically, the visualizations referred to herein are external visualizations, e.g., graphics, maps, diagrams, models, simulations, etc. These are distinguished from internal visualizations, i.e., internal mental constructs or mental models, used in reasoning (Johnson-Laird, 1985). (More on the role of mental models later in the paper). Furthermore, the visualizations of interest here are semantically-rich representations which involve complex, domain-specific symbol systems and as such are distinguished from iconic visual representations, e.g., a stop sign, which do not require a deep, conceptual knowledge base. Thus, the comprehension of and reasoning with semantically-rich visualizations is much more complex (Gobert, 1994). Because of the complexity involved in understanding geological maps, Geology is an excellent domain in which to think about the human cognition underlying visualizations.

In general, comprehending or interpreting complex visualizations is difficult because all the information is presented to the learner simultaneously in contrast to textual information sources in which the information follows the structure of the text (Larkin & Simon, 1987). For more details on the information-processing ramifications of these differences, see Gobert, 2005 (in press). In the case of graphics in geology, another level of complexity is added because 3-dimensional information is represented in 2-dimensional form. Thus, in order to understand a terrain from a geological map for example, learners must be able to make inferences about 3-dimensional features from 2-dimensional information depicted by differing line types and hierarchies of pen weights. This is a complex and non-trivial task similar to understanding a building as a 3-dimensional entity from it plans which depict this information in 2-dimensions in architectural plans (Gobert, 1994, 1999).

In unpacking the learning processes from visualizations in Geology, the literature from Cognitive Science provides an excellent framework for both research and teaching with visualizations. The next sections of this paper are dedicated to this goal.

Cognitive science literature as a framework for research and teaching with visualizations in Geology

In thinking about learning processes for visualization, learning is viewed as an active and constructive process. This view of learning is largely due to a seminal paper entitled "Levels of processing: A framework for memory research" (Craik & Lockhart, 1972; Lockhart & Craik, 1990) which introduced the notion that the nature of the learner's processing of the stimulus material largely determines the learner's memory representations for that material. The levels of processing framework was originally developed for text materials, but the framework has been subsequently shown to be applicable with visual stimuli, including faces (Bower & Karlin, 1974) and cartoon figures (Bower, Karlin, & Dueck, 1975), as well as complex conceptual visual stimuli such as those found in chess (Lane & Robertson, 1979) and architecture (Akin, 1978, 1979; Gobert, 1989, 1994, 1999).

Expert-novice literature. A great deal of what is known about visual information processing has come from the expert-novice literature both in terms of how domain-related information is stored and chunked in human memory and the ways in which information processing is directed by prior domain knowledge. Differences between experts and novices have been studied in many, diverse domains including computer programming (Adelson, 1981, 1984; McKeithen, Reitman, Reuter & Hirtle, 1981), algebra (Lewis, 1981), physics (e.g., Chi, Feltovich & Glaser, 1981; Chi, Glaser & Rees, 1982' Larkin et al, 1980), and medicine (Frankel Tal, 1992; Groen & Patel, 1988; Patel & Groen, 1986; Patel et al, 1990; Patel et al, 1984). Bereiter and Scardamalia (1993) and Ericsson and Smith (1990) provide a good review of this literature.

In terms of previous research on expertise, relatively few of the studies deal with visual information sources (compared to the total number of expertise studies conducted). Some of these studies include research in the following domains: chess (Chase & Simon, 1973; deGroot, 1965, 1946/1978), Go (Reitman, J., 1976), gomoku (Eisenstadt & Kareev, 1975), bridge (Charness, 1979), radiology (Lesgold, et al., 1988; Myles-Worsley, Johnston, & Simons, 1988), geographical map reading (Ormrod et al., 1986; Gilhooly et al., 1988; Thorndyke & Stasz, 1980), topographical map reading (Chang et al., 1985); architecture (Akin, 1979; Chase & Chi, 1981; Gobert, 1989; 1994), electronics (Egan & Schwartz, 1979), and engineering (Vicente, 1991, 1992; Bedard, 1993).

In terms of expertise studies in semantically-rich domains like geology, a few studies have been conducted. Egan and Schwartz (1979) used a recall task to examine differences in chunking of information from electronic circuit diagrams between novices and experts in electronics. In addition to recalling larger chunks, skilled electricians related some of the chunks together and used their conceptual knowledge of the function of the various circuits in order to structure their recall. Furthermore, it was suggested that their knowledge organization was attributable to the functional units they had identified during their initial learning of the circuit diagram.

Ormrod, Ormrod, Wagner, and McCallin (1986) used faculty from geography, educational psychology, and sociology in order to examine their respective abilities to learn and recall two maps: a logical one (based on geographical principles), and an illogical one (the elements were randomly placed). Geographers, having a great deal of knowledge about map features, were hypothesized to use their domain knowledge to organize the map features in a meaningful way. Educational psychologists were chosen for their knowledge related to memory and learning principles. A control group of sociologists was also added. Results for the logical map showed that the best performance was attained by geographers, followed by educational psychologists; however, in the case of the illogical map, the recall of all three groups of subjects was equally low. Thus, the geographers, being "map experts", applied principles from their domain in order to learn the chosen map; educational psychologists, whose recall was greater than the sociologists, applied principles from their domain, e.g., memory and learning strategies in order to learn the map. Similarly, in the case of topographic map reading (Chang et al., 1985; Gilhooly et al., 1988; Eastman, 1985) experts were found to have better comprehension of relative heights of the terrain depicted in the map. Search strategies identified by eye-tracking showed that they attended to the highest and lowest points depicted (implicitly) in the map in order to fully understand the terrain (Chang et al., 1985).

In studies conducted in architecture, experts were found to represent their knowledge in hierarchical structures made up of spatial chunks (Akin, 1979; 1986; Chase & Chi, 1981) and that the nature of the learning processes employed affected the resulting conceptual representations (Akin, 1979; 1986). In a study involving the understanding of a building from its plans, experts were found to better understand the building as a 3-dimensional entity compared to their less expert counterparts and that experts also employed more sophisticated search strategies in that they were both more systematic and 3-dimensional compared to sub-experts. Again, the resulting understanding of the building in both groups was found to reflect their initial knowledge acquisition strategies (Gobert, 1994; 1999).

Important in all of these studies is the finding that experts used knowledge acquisition strategies for learning from visualizations that are highly related to required task performance in their respective domain. Thus, in each case, skills for acquiring knowledge from visual information sources have evolved through experience and are especially adapted for performance in their respective domain. This domain-specific prior knowledge used in acquiring knowledge from visual information sources are referred to as schemata

(Brewer & Nakamura, 1984; Schank & Abelson, 1977; Rumelhart & Norman, 1975) which provide perceptual and cognitive structures that influence the amount and manner in which information is acquired and encoded in memory such that experts can process domain-specific material to a deeper level these prior knowledge schemata also account for the superior recall and inference-making evidenced by experts when they are working in their domains of expertise (Chang, Lenzen, & Antes, 1985; Gilhooly et al., 1988; Head, 1984).

Approaches to eliciting deep processing of visual information sources. Deep processing of information is a necessary requirement for conceptual understanding, and thus, much of the research which is carried out in cognitive science and education has higher level learning as its goal. One approach to eliciting deeper processing is providing students with orienting tasks (cf., Craik & Lockhart, 1972; Schmalhofer & Glavanov, 1986). Orienting tasks are instructions given to learners as part of the task in order to structure the learners' knowledge acquisition and processing. Orienting tasks for processing target material have significant effects on learning for both simple (Schulman, 1971) and complex textual material (cf., Schmalhofer & Glavanov, 1986). Results from studies using orienting tasks have shown that the beneficial effects on learning are greatest when the learner's attention is brought to features of the target material which would not be attended to otherwise, or when orienting tasks lead learners to engage in methods of learning which they would not use spontaneously, particularly learners lacking specific domain-knowledge (Mayer, 1989).

Implications for understanding visual information sources from text comprehension. As previously mentioned, information about objects or processes may be presented in either visual or textual form. Although the comprehension processes for textual information sources is fairly well understood (Frederiksen et al, 1988; Kintsch, 1988), very little is know about the comprehension processes for visual information sources. Briefly, models of text comprehension propose that understanding a text is a stratified process in which the semantic information presented in a text is represented by the learner in several levels. The comprehension process also inference-making from the information explicitly represented in the text by the learner (Frederiksen, Bracewell, Breuleux, & Renaud, 1989; Frederiksen & Breuleux, 1988; Kintsch, 1986, 1988; vanDijk & Kintsch, 1983). The three levels of representation hypothesized are (Frederiksen, Bracewell, Breuleux, & Renaud, 1989; Frederiksen & Breuleux, 1988; Kintsch, 1986, 1988; vanDijk & Kintsch, 1983):

(a) **the linguistic/syntactic level** which reflects the syntactic structure of the text and word/morpheme sequences upon which the syntactic parsing is performed.

(b) **the propositional level** which reflects the semantic information presented in the information source. The propositional level is regarded as an intermediate semantic level of representation, and

(c) **the conceptual level** which refers to a higher -level of semantic representation also called situation models (Kintsch, 1988) or mental models (Johnson-Laird, 1985) and are postulated to be the way in which information is represented in long-term memory.

Using these theories of comprehension, methods for coding learners' understanding have been developed (Frederiksen, 1975, 1986; Frederiksen, Bracewell, Breuleux, & Renaud, 1989) and can be successfully used to code the conceptual information contained in a textual/linguistic information source as well as to code learners' understanding of various types of information sources, including visualizations which expressed in natural language, such as think aloud protocols from learners. For example, Frederiksen's propositional model has been used to represent the understanding of complex semantic information in: chemical equations (Kubes, 1988; Frederiksen & Renaud, 1989), algebraic expressions (Frederiksen & Renaud, 1989), a text describing plate tectonics (Gobert & Clement, 1999), think aloud protocols about architectural plans (Gobert & Frederiksen, 1988; Gobert, 1989), and think aloud protocols about electronics diagrams (Bedard, 1993). Thus, in terms of semantically-rich visualizations, the working hypothesis here is that similar cognitive processes used in the comprehension of textual material also should operate in the comprehension of graphic information sources (Gobert, 1994). (It is important to note that there are likely modality-specific levels of representation also required in the comprehension of visual information sources).

In two of the studies presented herein, text is used as a learning source, thus, the text comprehension model and methods of coding are appropriate for these data. Levels 2 and 3, the propositional level and resulting conceptual representation (both described above), are the levels of representation we are concerned with for the purposes of this research. As predicted by the comprehension model, simple recall and recognition tasks are best supported by the representation of the propositional information contained in the text, i.e. level 2. Inference-making and reasoning tasks, reflecting higher-level understanding, are best supported by representations which reflect higher level, more integrated representations, i.e., situation models or mental models (Johnson-Laird, 1985), level 3 (described above).

Model-based teaching & learning as a framework for learning with visualizations in Science. Compatible with the text comprehension framework above (but at a more general level of description) is a framework called Model-based teaching and learning (Gobert & Buckley, 2000) which underlies much of the student conception work on model-based reasoning in Science Education.

Model-based learning and teaching is a theory about science learning based on a synthesis of research in Cognitive Psychology (including text comprehension) and Science Education (Gobert & Buckley, 2000). In model-based teaching and learning, it is assumed that learners construct mental models, i.e., internal visualizations, of phenomena in response to a particular learning task (assuming the task has engaged the learner); these are thought to be in the mind's eye and used in mental imagery and to solve problems whereby people read off their mental model (Johnson-Laird, 1985). In learning science, the model that is constructed integrates pieces of information about the spatial structure of the object, the causal mechanisms involved in the process under inquiry, and other relevant features of the process. Reasoning with the 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. Model-based reasoning requires modeling skills to understand representations, generate predictions and explanations, transform knowledge from one representation to another, as well as analyze data and solve problems.

Types Knowledge and Models in Plate Tectonics.

In thinking about Geology from a pedagogical point of view, it is productive to identify the types of knowledge one needs in order to understand geological phenomena. A useful approach to thinking about Plate Tectonics was framed as a part of earlier work (Gobert, 2000) in which propositional analysis (Frederiksen, 1985) was conducted on an explanatory text about Plate Tectonics. (Propositional analysis is a method of semantic analysis by which the smallest units of meaning are identified and then a semantic network model is constructed which allows the experimenter to evaluate the learner's knowledge about the text, and in turn, assess the types and respective amounts of knowledge which the learner has acquired either from the text or on the basis of inferences on the text.) Here, three types of knowledge were derived (it is likely that these apply to other sub-domains of Geology as well): **spatial knowledge**, i.e., the spatial structure of a geological object; in the case of Plate Tectonics, the inside structure of the earth, **causal knowledge**, i.e., causal mechanisms underlying Plate tectonic phenomena, e.g., convection currents, and **temporal knowledge**, i.e., knowledge about the time scale of different geological phenomena (continental drift versus volcanic eruption). Thus, in teaching Plate Tectonics, it is reasonable to assume that breaking down the conceptual knowledge into these types would elicit deep learning. Additionally, in deciding on the order of presentation of conceptual knowledge, we used a progressive model-building approach in which simpler conceptual knowledge provides conceptual leverage for more complex types of knowledge. The pedagogical strategy of progressive model-building has been shown to be successful for supporting students' learning in physics in which simpler models of density and force addition provided conceptual leverage for understanding buoyancy (Raghavan & Glaser, 1995). Additionally this approach has been successful for electricity (White & Frederiksen, 1990) and Newtonian Mechanics (White, 1993) in which students learn a series of causally more complex models. In the studies to be presented later in this paper, we used this progressive model-building approach in which we first had students think about the spatial structure of the earth, then we engaged them in thinking about causal and dynamic processes inside the earth, lastly, we engaged them in thinking about two plate tectonic-related phenomena, namely mountain formation and volcanic eruption, as two real-world examples of plate tectonic phenomena.

Science education work on student conceptions in Geology. The topic of learning in Earth Science has not been well studied, particularly when compared to students' learning and conceptions in the physical sciences (Stofflett, 1994). The lack of research on learning in the Earth Sciences is likely due to the fact that in the past, it has received much less emphasis than the Physical and Life Sciences in national and state curricular standards. Now however, the National Science Education Standards (1996) are recognizing Earth

Science as a necessary and important component of science training across elementary, middle, and high school levels and considered equivalent in importance to training in the Life and Physical sciences (AAAS, 1989, 1993).

The importance of learning in this domain is reflected in a number of more recent projects on Earth Science covering both teacher professional development projects (cf., Mayer, Fortner, & Hoyt, 1995) and student cognition projects including: knowledge of the causes for earthquakes (Ross & Shuell, 1993; Bezzi, 1989; Turner, Nigg, and Daz, 1986), mountain formation (Muthukrishna et al, 1993), knowledge of the earth as a cosmic body (Vosniadou & Brewer, 1992, Nussbaum, 1979, Nussbaum & Novak, 1976; Sneider & Pulos, 1983), knowledge of rock-cycle processes (Stofflett, 1994), conceptions of earth and space as it relates to seasons and phases of the moon, (Schoon, 1992; Bisard et al, 1994), conceptions of sea floor dynamics (Bencloski and Heyl, 1985), knowledge of the earth's gravitational field (Arnold, Sarge, and Worrall, 1995), and knowledge of the scale of the earth (Ault, 1994). There are also some recent programs of research that utilize visualizations in Plate Tectonics for student learning, including the Visual earth project (www.tercworks.terc.edu), the Science Odyssey project (www.pbs.org/wgbh/aso/tryit/tectonics), the Visualizing Earth project (www.visearth.ucsd.edu), and the Princeton Earth Physics Project, a high school and college-based project which uses an array of seismographs for the study of earthquakes (http://lasker.princeton.edu). However, none of these existing programs (to our knowledge) seeks to address the plate tectonics in an integrated fashion; that is, some emphasize sea floor spreading, earthquakes, volcanoes, etc., but none integrate all types of plate tectonic phenomena. Additionally, none of these explicitly emphasize *active model building* on the part of the students.

Plate Tectonics as a sub-domain of study. As previously mentioned, Plate Tectonics is an excellent domain in which to investigate students' model-based learning because of the plethora of models, (i.e., external visualizations) used in Geology and the important role that model building, (as an internal mental activity) plays in understanding geological phenomena of hidden mechanisms, e.g., convection underlying continental drift, earthquakes, volcanoes, mountain formation, and sea floor spreading.

Plate tectonics, which is typically covered in fifth or sixth grade and then again in eighth or ninth grade is representative of a difficult school science topic. It is difficult to learn for many reasons: 1) the earth's internal layers are outside our direct experience, 2) the size scale and the unobserved processes, e.g., convection, are difficult to understand (Ault, 1984; Gobert & Clement, 1994; 1999), 3) the time scale of geological processes is difficult for people to conceptualize since it surpasses our reference of a human lifetime (Jacobi et al., 1996), and 4) it involves the comprehension and integration of several different types of information, such as, spatial, causal, and dynamic (Gobert & Clement, 1994; 1999).

Research on Fostering Students' Models and Reasoning in Plate Tectonics. Previous research addressing model-based learning in plate tectonics include: the effects of a multimedia environment, CSILE (Scardamalia & Bereiter, 1991), on students' graphical and causal explanations of continental drift (Gobert & Coleman, 1993); learning difficulties encountered in this domain (Gobert & Clement, 1994); the nature of students' pre-instruction models and associated causal reasoning (Gobert, 2000); the benefits of student-generated diagrams versus summaries (Gobert & Clement, 1999); the influence of students' epistemologies of models on learning in this domain (Gobert & Discenna, 1997); and students' on-line collaboration about plate tectonics (mtv.concord.org; Gobert, 1998; Gobert & Pallant, 2004). Research most relevant to the topic of model-based learning in Earth Science are reviewed briefly in turn.

Previous Research, Study 1: Students' pre-instruction models and learning difficulties.

Gobert and Clement (1994) investigated fifth grade students' pre-instruction models of plate tectonics by conducting one-on-one interviews with children. Students' diagrams and think aloud protocols (Ericsson & Simon, 1980) were examined as a reflection of their mental models. Three main difficulties were identified in students' model construction processes: (1) problems with setting up a correct static model of the layers, (2) difficulty understanding causal and dynamic information (e.g., heat as causal in forming convection currents, or currents causing plate movement), and (3) difficulties with the integration of several different types of knowledge including causal and dynamic knowledge into a causal chain in order to build an integrated mental model of the system.

Based on protocol analyses of middle school students' diagrams and interview data (Ericsson & Simon, 1980) as well as data from classroom research (Gobert & Clement, 1994; 1999), two types of student models of the inside of the earth were identified at this age level (see figure 1 and table 1 below). These models (below) were drawn in response to the prompt, "Draw a diagram of the different layers of the earth".

Insert figure 1 and table 1 here

Based again on protocol analyses of middle school students' diagrams and interview data (Ericsson & Simon, 1980) as well as data from classroom research (Gobert & Clement, 1994; 1999), four types of student models of the inside of the earth were identified at this age level (see figure 2 and table 2 below). These models were drawn in response to the prompt, "Draw a diagram to depict what happens in the different layers of the earth when a volcano erupts". The models (below) are on a continuum from Type 1a and 1b reflecting models with only heat-related mechanisms and movement-related mechanisms, respectively, as the primary causal mechanisms responsible for volcanic eruption to Type 3 models which integrate multiple heat-related and movement-related causal mechanisms thus, reflecting the most sophisticated model observed at this age level. An integrated model in the case of volcanic eruption, for example, refers to one in which students have integrated their spatial model of the earth with a number of causal and dynamic mechanisms (i.e., core as a heat source, convection currents pushing on plates, plates moving apart, and magma rising above the surface). It is assumed that from these rich causal models, inferences can be made about the causal mechanisms involved in other plate tectonic phenomena, e.g., sea floor spreading, etc.

Insert figure 2 and table 2 here

Model-Based Reasoning afforded by different types of models. Further analyses of students' models and think aloud protocols (Gobert, 2000) were used to demonstrate that if the student correctly depicts (i.e., understands) the layers of the earth in a spatial layout of concentric circles, then they are better able to revise this model to include (and understand) the causal and dynamic processes in the earth. If, alternatively, the student has a spatially incorrect model of the earth, this model will need to be revised before the model will support reasoning and inference-making by means of perceptual cues such as spatial adjacency (Larkin & Simon, 1987), e.g., one student (see Gobert, 2000) had a spatially incorrect model of the earth (such as Type 0 in Figure 1) which could not support the understanding of convection currents. By contrast, it was also shown that spatially correct models can serve as tools for reasoning (Kindfield, 1993) and model revision, e.g., another student who had a spatially correct model of the interior of the earth (such as Type 1 in Figure 1) made the correct inference that because the core was hot and the mantle was beside the core, the core acts as a heat source for the magma (see Gobert, 2000). (It is important to note that the goal in this program of research is to facilitate students' understanding of plate tectonics by means of qualitative, simplified models. As such, issues like whether radioactive decay in the mantle acts, in part, as a heat source in addition to the earth's core are not addressed in middle school but can be addressed in high school.)

Previous Research, Study 2. Promoting model-based learning: diagramming versus summarizing as an orienting task for deep science learning.

Based on the analyses from Study 1 it was hypothesized that understanding of the different types of information in this domain (i.e., spatial, causal/dynamic), as well as model construction is facilitated by diagram-based learning elicited in a progressive model-building order. This hypothesis was also based on previous research that has shown that diagrams both permit inferences based on perceptual cues such as spatial adjacency (Larkin & Simon, 1987) and explicitly indicate structural relationships (Schwartz, 1993) which are difficult from textual representations.

We tested empirically the efficacy of two different orienting tasks, namely, student-generated diagrams versus student-generated summaries as means to foster the development of rich, integrated models like the Type 3 models achieved in Study 1 described above. More specifically, here we investigated whether the task of constructing diagrams while reading would promote the development of richer causal models when compared to the task of generating summaries.

Two groups of students were asked to either construct diagrams or summaries at four specific points during their reading of a text describing plate tectonics; a control group who read the text only was also included. After students had read the text, they were given a written post-test that assessed both spatial/static knowledge and causal/dynamic knowledge. There were two sets of data generated: the intermediate data (diagrams or summaries) which reflect students' understanding of the text, and a set of post-test data, which reflect students' higher-level conceptual understanding of the domain. In accordance with the text comprehension model underlying this research (van Dijk & Kintsch, 1983), simple recall and recognition tasks are best supported by a memory for the text itself, i.e., a text-base of the propositional knowledge contained in the text whereas, higher-level inference tasks are best supported by higher level, more integrated representations, i.e., situation models (Kintsch, 1988) made on the basis of the text plus inferences made on the text. In accordance with this theory, it is assumed that the understanding that the students exhibit on the post-test is due to an interaction of the processing induced by the orienting task (presented to the students before the relevant paragraphs) of either diagram-drawing or summarizing with the processing of the main passage itself.

Analysis of summaries and diagrams as intermediate representations. An overall manova on the semantic content comparing the summaries and diagrams on each of the four intermediate tasks revealed statistically significant differences favoring the summary group ($F = 5.718$, $p = .001$). (Since the coding scheme is based on semantic information regardless of medium, the coding scheme can be applied to either summaries or diagrams (Gobert, 2000). In terms of these findings, the intermediate representations, the **summary group outperformed the diagram group**, i.e., the summaries contained more semantic information than did the diagrams (see Gobert & Clement, 1999 for details on these data).

Analysis of post-test scores as mental model representations. A manova of the post-test revealed significant differences between the three groups (diagram, summary, control) for both the understanding of spatial information ($F = 4.38$, $p < .05$) as well as the understanding of causal/dynamic information ($F = 4.31$, $p < .05$). Thus, in terms of the students' resulting conceptual understanding, **the diagram group outperformed the summary group** and there were no significant differences found between the summary group and the control group (see Gobert & Clement, 1999 for details on these data).

This "discrepancy" between the findings for the intermediate tasks (summary group >diagram group) and the post-test (diagram group >summary group) was interpreted as follows. For the summary group, because the media was the same (textual information source and textual summarization task), they were able to rely on rote memory of what they had just read in order to produce their summaries, as evidenced by the inclusion of more semantic information than the diagram group on the intermediate tasks. However, the summarization task, because it only elicited only rote processing of the text, did not promote inferencing or mental model construction, as evidenced by poorer performance on the post-test than the diagram group. For the diagram group, these data suggest that constructing diagrams as part of the reading task required the students re-represent their knowledge into a diagrammatic format, and that they could not solely rely on rote memory of the text to do this, as evidenced by lower scores on the intermediate tasks. More specifically, diagramming required inferences in order to restructure what they read into diagrammatic representations, and this processing lead to an advantage in terms of the resulting conceptual understanding. These findings are consistent with van Dijk and Kintsch's (1983) theory of text comprehension, as well as studies which have shown that learner's representations of material can be altered by changing their goals for learning (Schmalhofer & Glavanov, 1986).

However, an empirical question remained as to whether a different orienting task would elicit a deeper processing of the text compared to diagramming as an orienting task. A study which utilized a higher-level orienting task (higher level than summarizing) during reading would test the hypothesis whether it was the diagrammatic medium in particular or inferencing in general which was supporting mental model construction and higher-level reasoning yielded by those in the diagram condition in Study 2.

Study 3: The Effects of Diagramming versus Explaining on Text-based Representations and Mental Models.

Here, constructing diagrams as an orienting task during reading was compared to constructing explanations during reading. The choice of explanation as an orienting task was influenced by work which has shown that knowledge integration in science can be facilitated by providing an explanation to others (Coleman, 1992, 1995), as well as by providing self-explanations (Chi et al, 1994). Chi and her colleagues have suggested, although not empirically demonstrated, that explanation-based activities are likely to promote the same type of inferences as diagram-drawing. Thus, in this study we sought to test out whether it was the "translation" of the textual information into diagrammatic representations which influenced students' conceptual gains yielded on the post-test from Study 2 (above) or whether a higher level orienting task might elicit deep levels of processing and inference-making and thus higher conceptual understanding on the post-test.

Subjects. Two classes of grade five students participated. The students ranged in age from 10 to 12 years. Students were drawn from a small town in western Massachusetts, more specifically, from the same school and teacher, as in Study 2, thus it is reasonable to assume that they represent the same demographic.

Procedure. Students were given a short text (about 2 pages) about Plate Tectonics. One group was asked to draw diagrams at specific points during the text, and one group was asked to write explanations at the same points during the text. The prompts to draw or explain were given prior to each section of the text. For example, "After this paragraph, you will be asked to draw a diagram of the different layers of the earth". Thus it is assumed that the students' processing of the text interacts with the orienting task that the students were given.

For both groups the orienting tasks were requested in order of increasing difficulty, as in Study 2 (above), to promote progressive model-building. The instructions given to the subjects were as follows:

Explanation 3) "After this paragraph you will be asked to explain what happens in the different layers of the earth when mountains are formed. Include all the information about these layers that you can so that a friend who had never heard of this could learn about it."

OR

Diagram 3) " After this paragraph you will be asked to draw a picture of the different layers of the earth when mountains are formed. Include and label all the information about these layers that you can so that a friend who had never heard of this could learn about it."

The orienting tasks were requested of the groups were: 1) depict/explain the different layers of the earth; 2) depict/ explain the causal processes which are occurring in these layers; and 3) depict/explain what happens in the layers of the earth when mountains are formed.

Coding of data. Coding schemes were developed for each of the three orienting tasks; the scheme was used to code the diagrams and explanations for the inclusion of propositional information from the text source. More information about this type of coding scheme can be found in Gobert (2000). Using these data, the two groups were compared in terms of the semantic information contained in their explanations and diagrams during their reading of the text, as in Study 2; again, these data reflect their intermediate representations of the text.

The two groups were compared on their post-test, i.e., their resulting conceptual representations for the spatial as well as causal and dynamic aspects of the domain; again, this reflects their resulting conceptual understanding of the text plus inferences made on the text, i.e., their mental models.

Results

Analysis of explanations and diagrams as intermediate representations. For the comparison of the semantic information contained in explanations and diagrams which were generated during the students' reading of the text, a Manova yielded no statistically significant differences between the two groups (F= 1.31, p= .283 (Wilks); n.sig.). See the table below for the univariate Fs and the means.

Insert table 3 here

Analysis of post-test data. A Manova was performed with both spatial and causal dynamic understanding entered as variables. No statistically significant differences were obtained at either the multivariate [F = 1.89, p=.162; n. sig.] or univariate level for either the measure of the spatial layers of the earth [F= 1.05, p=.310; n. sig.], or the causal and dynamic processes involved in plate tectonics [F = .075, p=.785; n. sig.]. See Tables 4 and 5 for means and standard deviations.

Insert tables 4 & 5 here

Summary of results from Study 3. The explanations and diagrams that were constructed during students reading of the text contained approximately similar amounts of semantic information. In terms of the resulting conceptual representations, both groups also scored equally well in terms of their understanding of both the spatial layout of the layers of the earth as well as the causal and dynamic processes in the layers.

Discussion and Conclusions

In this paper relevant literature from Cognitive Science and Science Education are presented as a framework for thinking about learning and teaching with semantically rich-visualizations, such as those used in the Geology. Specifically, studies addressing expertise in learning with visually-complex representations are presented, as well as are findings about how to elicit deep processing of visually complex representations. Models of text comprehension are briefly described as framework for thinking about the comprehension of semantically-rich visualizations. Propositional analysis, derived from models of text comprehension, is briefly described in terms of how it can be used to systematically code learners' understanding on the basis of their think aloud protocols, diagrams, or written text (i.e., summaries or explanations). Lastly, model-based learning and teaching is described as a theoretical synthesis of cognitive psychology and science education; this framework, applied in the present studies, underlies (either explicitly or implicitly) much of the research on students' conceptions and conceptual change in science.

Regarding research on learning with visualizations, three studies are presented. Study 1 is an example of the types of mental models students hold; the reasoning associated with different types of mental models is described elsewhere (Gobert, 2000). This study makes a contribution to the literature since the types of models that students hold at this age level provide insight into why learning in this domain is difficult. Also, these models represent the pre-instruction conceptions that students bring to instruction in Plate Tectonics, thus, these findings have pedagogical implications for teaching Plate Tectonics.

Studies 2 and 3 employ methodologies from Cognitive Science i.e., the comprehension framework, and the semantic analysis that was applied to students' articulated models (i.e., their diagrams) and to their summaries and/or explanations. The data from Study 2 demonstrated the superior effects of diagramming over summarizing at intermittent points during reading as means to promote deep processing of textual material. These findings were interpreted as the diagramming orienting task as having a representational advantage over the summary task since the diagramming task provided affordances for both developing better mental models of the domain, and using these models, once constructed, as inference-making devices (Kindfield, 1993/1994). A follow-up study, Study3, was conducted in order to test whether it was the visual medium of diagramming or inferencing in general that was driving the superior learning exhibited by the diagram group in Study 2. In this study, explanation was chosen as an orienting task (versus diagramming) as means to promote deep processing of the text since explaining requires a higher-level of processing than does summarizing (Chi et al, 1994; Coleman, 1992). The data here yielded interesting results, i.e., no differences were observed between the two groups on either their intermediate representations (as measured by the semantic information contained in their diagrams versus explanations) or their resulting understanding (as measured by the post-test). From these data, it is suggested that both types of orienting tasks, diagramming and generating explanations elicited deep processing on the part of the students. For example, it is possible that those in the explanation condition, i.e., who knew they were going to generate explanations at specific points in the text, were developing mental models in order think deeply about the information needed in their explanation, and thus, the processing affordances are similar to those who were in the diagram condition. However, based on these data, we can only speculate about the modality-specific versus modality-general processing mechanisms. Research is currently underway in order to examine possible reading time differences for the different orienting task conditions, namely, summarization, explanation, and diagramming (Gobert, 2002) in order to try to empirically tease out possible differences. If processing differences are found across these varying orienting tasks, these data will be used to infer the interaction between the nature of the orienting task, the modality-specific as well as the modality-general processes employed in constructing and revising mental models, and the processing of the text itself. Lastly, these data will contribute to the cognitive science literature in terms of processing differences and affordances for learning in the different information modes; these data contribute to Science Education in terms of the implications for instruction with these information modes.

Acknowledgements.

Figures 1 and 2 and Tables 1 and 2 and appeared previously in Gobert, J. (2000). A typology of models for plate tectonics: Inferential power and barriers to understanding. *International Journal of Science Education, 22(9),* 937-977 and are reprinted with permission from Taylor and Francis, Inc.

Studies1 & 2 were funded by a NSF grant awarded to John Clement. Study 3 was supported by a Spencer Post-Doctoral Award from the National Academy of Education awarded to Janice Gobert.

References

American Association for the Advancement of Science. (1989). *Science For All Americans*: *Project 2061*. Washington, D.C.: American Association for the Advancement of Science.

American Association for the Advancement of Science. (1993). *Benchmarks for Science Literacy*: 1993. New York Oxford: Oxford University Press.

Adelson, B. (1981). Problem-solving and the development of abstract categories in programming languages. *Memory and Cognition, 9,* 422-433.

Adelson, B. (1984). When novices surpass experts: The difficulty of a task may increase with expertise. *Journal of Experimental Psychology: Learning, Memory and Cognition, 10,* 483-495.

Akin, O. (1978). How do architects design? In J.-C. Latombe (Ed.), *Artificial intelligence and pattern recognition in computer aided design*. New York: North-Holland.

Akin, O. (1979). Models of architectural knowledge: An information-processing view of design. *Dissertation Abstracts International, 41*(3), p. 833 A. (University Microfilms No. 72-8621.)

Arnold, P., Sarge, A., & Worrall, L. (1995). Children's knowledge of the earth's shape and its gravitational field. *International Journal of Science Education, 17(5),* 635-641.

Ault, Jr., C. R. (1984). The everyday perspective and exceedingly unobvious meaning. *Journal of Geological Education, 32*, 89-91.

Bedard, D. (1993). *Utilisation des connaissance dans la résolution de problemes en électronique*. Unpublished doctoral thesis. McGill University, Montreal.

Bencloski, J. W., & Heyl, R. J. (1985). Teaching plate tectonics with the aid of a model of sea-floor dynamics. *Journal of Geological Education, 33*, 274-276.
Bereiter, C., and Scardamalia, M. (1993). *Surpassing ourselves: An inquiry into the nature and implications of expertise*. Chicago: Open Court.
Bezzi, A. (1989). Geology and society: A survey on pupil's ideas as an instance of a broader prospect for educational research in earth science. Paper presented as the 28th International Geological Congress, Washington, D.C.
Bisard, W. J., Aron, R. H., Francek, M. & Nelson, B. D. (1994). Assessing selected physical science and earth science misconceptions of middle school through university pre-service teachers. *Journal of College Science Teaching,* September/October, 38-42.
Board, C. (1984). Higher order map-using tasks: Geographical lessons in danger of being forgotten. *Cartographica, 21*, 85-97.
Bower, G., and Karlin, M.B. (1974). Depth of processing of pictures of faces and recognition memory. *Journal of Experimental Psychology, 103*, 751-757.
Bower, G., and Karlin, M.B., and Dueck, A. (1975). Comprehension and memory for pictures. *Memory & Cognition, 3,* 216-220.
Brewer, W., and Nakamura, G. (1984). The nature and functions of schemas. In R.S. Wyer and T.K. Skull (Eds.), *Handbook of Social Cognition, Volume 1*. Hillsdale, NJ: Lawrence Erlbaum.
Chang, K.-T., Lenzen, T., and Antes, J. (1985). The effect of experience on reading topographic relief information: Analyses of performance and eye movements. *The Cartographic Journal, 22*, 88-94.
Charness, N. (1979). Components of skill in bridge. *Canadian Journal of Psychology*, *33*, 1-50.
Chase, W., & Chi, M. (1980). Cognitive skill: Implications for spatial skill in large-scale environments. In J. Harvey (Ed.), *Cognition, social behavior, and the environment*. Potomac, MD: Erlbaum.
Chase, W., & Simon, H. (1973). The mind's eye in chess. In W.G. Chase (Ed.), *Visual information processing*. New York: Academic Press.
Chase, W., and Chi, M. (1981). Cognitive skill: Implications for spatial skill in large-scale environments. In J. Harvey (Ed.), *Cognition, social behavior, and the environment.*_ Potomac, MD: Lawrence Erlbaum.
Chase, W., and Simon, H. (1973). The mind's eye in chess. In W.G. Chase (Ed.), *Visual information processing*. New York: Academic Press.
Chi, M.T., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.
Chi, M.T., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 1). Hillsdale, NJ: Erlbaum.
Chi, M.T.H., de Leuw, N., Chiu, M. H., and LaVancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18(3),* 439-478.
Coleman E.B. (1992). *Facilitating conceptual understanding in science: a collaborative explanation-based approach.* University of Toronto, Unpublished doctoral dissertation.

Coleman, E. (1995). Learning by explaining: Fostering collaborative progressive discourse in science. In R. J. Beun, M. J. Baker, and M. Reiner (Eds.), *Natural dialogue and interactive student modeling*, Berlin, Germany: Springer-Verlag.

Craik, F.I.M., and Lockhart, R. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11*, 671-684.

de Groot, A. (1965). *Thought and choice in chess*. The Hague: Mouton.

de Groot, A. (1978). *Thought and choice in chess*. The Hague: Mouton. (Original work published in 1946).

Eastman, J.R. (1985). Cognitive models and cartographic design research, *The Cartographic Journal, 22,* 95-101.

Egan, D., and Schwartz, B. (1979). Chunking in recall of symbolic drawings. *Memory and Cognition, 7,* 149-158.

Eisenstadt, M., and Kareev, Y. (1975). Aspects of human problem-solving: The use of internal representations. In D.A. Norman and D. E. Rumelhart (Eds.), *Explorations in cognition*. San Francisco, CA: Freeman.

Ericsson, K., & Simon, H. (1980). Verbal reports as data. *Psychological Review, 87*, 215-251.

Ericsson, K.A., and Smith, J. (1991). Prospects and limits of the empirical study of expertise: An introduction. In K.A. Ericsson and J. Smith, (Eds.), *Toward a general theory of expertise: Prospects and limits*. Cambridge, MA: MIT Press.

Frankel Tal, N. (1992). *Diagnostic reasoning of difficult internal medicine case: Expert, proto-expert, and non-expert approaches*. Unpublished doctoral dissertation, University of Toronto, Toronto, Ontario.

Frederiksen, C. (1975). Representing logical and semantic structure of knowledge acquired from discourse. *Cognitive Psychology, 7*, 471-458.

Frederiksen, C. (1985). *Comprehension of different types of text structure*. Paper presented at the Annual Meeting of the Canadian Psychological Association, Halifax, Nova Scotia, Canada.

Frederiksen, C. (1986). Cognitive models and discourse analysis. In C. Cooper & S. Greenbaum (Eds.), *Written communication annual volume 1*: *Linguistic approaches to the study of written discourse*, Beverly Hills, CA: Sage.

Frederiksen, C. (1988). Text comprehension in functional task domains. In D. Bloom (Ed.*), Learning to use literacy in educational settings*. Norwood, NJ: Ablex.

Frederiksen, C., & Renaud, A. (1989, March). *Representation, acquisition and use of procedural knowledge in chemical engineering*. Paper presented at the American Educational Research Association annual meeting, San Francisco, California.

Frederiksen, C., & Breuleux, A. (1988). Monitoring cognitive processing in semantically complex domains. In N. Frederiksen, R. Glaser, A. Lesgold, & M. Shafto (Eds.), *Diagnostic monitoring of skill and knowledge acquisition*. Hillsdale, NJ: Erlbaum.

Frederiksen, C., and Renaud, A. (1989). *Representation, acquisition and use of procedural knowledge in chemical engineering*. Paper presented at the American Educational Research Association annual meeting, San Francisco, California.

Frederiksen, C., Bracewell, R., Breuleux, A., & Renaud, A. (1989). The cognitive representation and processing of discourse: Function and dysfunction. In Y. Joanette and H. Brownell (Eds.), *Discourse ability and brain damage: Theoretical and empirical perspectives*. New York: Springer-Verlag.

Frederiksen, C., Decary, M. & Hoover, M. (1988). The semantic representation and processing of natural language discourse: Development of a computational model. *Proceedings of the International Colloquium on "Informatique et langue naturelle."* Nantes, France.

Gilhooly, K.J., Wood, M., Kinnear, P.R., and Green, C. (1988). Skill in map reading and memory for maps. *The Quarterly Journal of Experimental Psychology, 40A (1),* 87-107.

Gobert, J. (1989). *The interpretation of architectural plans by expert and sub-expert architects*. Unpublished master's thesis. McGill University, Montreal, Canada.

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. (1999). Expertise in the comprehension of architectural plans: Contribution of representation and domain knowledge. In *Visual And Spatial Reasoning In Design '99*, John S. Gero and B. Tversky (Eds.), Key Centre of Design Computing and Cognition, University of Sydney, AU.

Gobert, J. (2000). A typology of models for plate tectonics: Inferential power and barriers to understanding. *International Journal of Science Education, 22(9),* 937-977.

Gobert, J. (2002). *Summarizing, Explaining, and Diagramming: The Differential Effects on Reading Times, Text-Base Representations, and Mental Models of Science Text.* Presented at the Winter Text Conference, Jackson Hole, WY, January 25-28.

Gobert, J. & Buckley, B. (2000). Special issue editorial: Introduction to model-based teaching and learning. *International Journal of Science Education, 22(9),* 891-894.

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

Gobert, J. & 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(1),* 39-53.

Gobert, J. & Coleman, E.B. (1993). Using diagrammatic representations and causal explanations to investigate children's models of continental drift. *Proceedings of the Society of Research in Child Development*. March 25-28. New Orleans, LA.

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

Gobert, J. & 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. Hillsdale, NJ.: Lawrence Erlbaum.

Gobert, J., and Frederiksen, C. (1989). *Expert and novice semantic interpretation of architectural drawings*. Paper presented at the Annual Meeting of the American Educational Research Association, March,. San Francisco, California.

Gobert, J.D., & Pallant, A., (2004). Fostering students' epistemologies of models via authentic model-based tasks. *Journal of Science Education and Technology. Vol 13(1),* 7-22.
Groen, G., and Patel, V. (1988). The relationship between comprehension and reasoning in medical expertise. In Chi, M.T.H., Glaser, R., and Farr, M. (Eds.), *The Nature of Expertise*. Hillsdale, NJ: Lawrence Erlbaum.
Head, C. (1984). The map as natural language: a paradigm for understanding. *Cartographica, 31*, 1-32.
Jacobi, D., Bergeron, A., & Malvesy, T. (1996). The popularization of plate tectonics: presenting the concepts of dynamics and time, *Public Understanding in Science, 5*, 75-100.
Johnson-Laird, P.N. (1985). Mental models. In A. Aitken, and J. Slack (Eds.), *Issues in cognitive modelling*. London: LEA Publishers.
Kindfield, A.C.H. (1993/1994). Biology Diagrams: Tools to think with. *Journal of the Learning Sciences, 3(1),* 1-36.
Kintsch, W. (1974). *The representation of meaning in memory*. Hillsdale, NJ: Lawrence Erlbaum.
Kintsch, W. (1986). Learning from text. *Cognition and Instruction, 3(2),* 87-108.
Kubes, M. (1988). *The use of prior knowledge in integration of information from technical materials*. Unpublished doctoral dissertation. McGill University, Montreal.
Lane, D., and Robertson, L. (1979). The generality of the levels of processing hypothesis: An application to memory for chess positions. *Memory & Cognition, 7(4),* 253-256.
Larkin, J. & Simon, H. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science, 11*, 65-100.
Larkin, J., McDermott, J., Simon, D., & Simon, H. (1980). Expert and novice performance in solving physics problems. *Science, 208,* 1335-1342.
Lesgold, A., Rubinson, H., Feltovich, P., Glaser, R., Klopfer, D., and Wang, Y. (1988). Expertise in diagnosing x-ray pictures. In Chi, M.T.H., Glaser, R., and Farr, M. (Eds.), *The Nature of Expertise*. Hillsdale, NJ: Lawrence Erlbaum.
Lockhart, R., and Craik, F.I.M. (1990). Levels of processing: A retrospective commentary on a framework for memory research. *Canadian Journal of Psychology, 44(1),* 87-112.
Mayer, V.J., Fortner, R.W., and Hoyt, W. H. (1995). Using cooperative learning as a structure for Earth Systems Education workshops. *Journal of Geological Education, 43,* 395-400.
Mayer, R. (1989). Systematic thinking fostered by illustrations in scientific text. *Journal of Educational Psychology, Vol. 81(2),* 240-246.
Muthukrishna, N., Carnine, D., Gressen, B., & Miller, S. (1993). Children's alternative frameworks: Should they be directly addressed in science instruction? *Journal of Research in Science Teaching, 30(3),* 233-248.
Myles-Worsley, M., Johnston, W., and Simons, M. (1988). The influence of expertise on x-ray image processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14(3),* 553-557.

National Committee on Science Education Standards and Assessment. (1996). *National Science Education Standards: 1996*. Washington, D.C.: National Academy Press.
Nussbaum, J. (1979). Children's conceptions of the earth as a cosmic body: a cross age study. *Science Education, 63*, 83-93.
Nussbaum, J. & Novak, J. D. (1976). An assessment of children's concepts of the earth utilizing structured interviews. *Science Education, 60*, 535-550.
Ormrod, J., Ormrod, R., Wagner, E., & McCallin, R. (1986, April). Cognitive strategies in learning maps. Paper presented at the Annual Meeting of the American Educational Research Association. San Francisco, CA.
Patel, V., & Groen, G. (1986). Knowledge-based solution strategies in medical reasoning. *Cognitive Science, 10*, 91-116.
Patel, V., Groen, G., and Arocha, J. (1990). Medical expertise as a function of task difficulty. *Memory & Cognition, 18(4),* 394-406.
Patel, V., HoPingKong, H., and Mark, V. (1984). Role of prior knowledge in comprehension of medical information by medical students and physicians. *Proceedings of Research in Medical Education*. Chicago: Association of American Medical Colleges.
Raghavan, K. & Glaser, R. (1995). Model-based analysis and reasoning in science: The MARS curriculum. *Science Education, 79,* 37-61.
Reitman, J. (1976). Skilled perception in GO. *Cognitive Psychology, 8,* 336-356.
Ross, K. & Shuell, T. (1993). Children's beliefs about earthquakes. *Science Education*, *77*, 191-205.
Rumelhart, D., & Norman, D. (1975). The active structural network. In D. Norman, D. Rumelhart, and the LNR Research Group (Eds.), *Explorations in cognition*. San Francisco, CA: W.H. Freeman.
Scardamalia, M & Bereiter, C (1991). High levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *Journal of the Learning Sciences, 1(1),* 37-68.
Schank, R., & Abelson, R. (1977). *Scripts, plans, goals, and understanding*. Hillsdale, NJ: Lawrence Erlbaum.
Schmalhofer, F., and Glavanov, D. (1986). Three components of understanding a programmer's manual: verbatim, propositional and situational representations. *Journal of Memory and Language, 25,* 279-294.
Schoon, K. J. (1992). Students' Alternative Conceptions of Earth and Space. *Journal of Geological Education, 40*, 209-214.
Schulman, H. (1971). Similarity effects in short-term memory. *Psychological Bulletin, 75*, 399-415.
Schwartz, D. (1993). The construction and analogical transfer of symbolic visualizations. *Journal of Research in Science Teaching, 30*, 1309-1325.
Sneider, C. & Pulos, S. (1983). Children's cosmologies: understanding the earth's shape and gravity. *Science Education, 67*, 205-221.
Spilich, G., Vesonder, G., Chiesi, H., & Voss, J. (1979). Text processing of domain related information for individuals with high and low domain knowledge. *Journal of Verbal Learning and Verbal Behavior, 18,* 275-290.

Spiro, R. (1977). Remembering information from text: The "state of schema" approach. In R. C. Anderson, R. J. Spiro, and W. E. Montague (Eds.), *Schooling and the acquisition of knowledge*. Hillsdale, J: Erlbaum.

Spiro, R. (1980). Constructive processes in prose comprehension and recall. In R. Spiro, B. Bruce, and W. Brewer (Eds.) *Theoretical issues in reading comprehension*. Hillsdale, NJ: Lawrence Erlbaum.

Stofflett, R. (1994). Conceptual change in elementary school teacher candidate knowledge of rock-cycle processes. *Journal of Geological Education, 42,* 494-500.

Thorndyke, P., & Stasz, C. (1980). Individual differences in procedures for knowledge acquisition from maps. *Cognitive Psychology, 12*, 137-175.

Turner, R. H., Nigg, J. M., & Daz, D. H. (1986). *Waiting for disaster: Earthquake watch in California*. Berkeley, CA: University of California.

van Dijk, T. & Kintsch, W. (1983). *Strategies of discourse comprehension*. New York: Academic Press.

Vicente, K. (1991). *Supporting knowledge-based behavior through ecological interface design*. Unpublished doctoral dissertation. University of Illinois, Chicago.

Vicente, K. (1992). Memory recall in a process control system: A measure of expertise and display effectiveness. *Memory & Cognition, 20(4),* 356-373.

Vosniadou, S. & Brewer, W. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*, 535-585.

White, B. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction*, *10 (1),* 1-100.

White, B. & Frederiksen, J. (1990). Causal model progressions as a foundation for intelligent learning environments. *Artificial Intelligence*, *24*, 99-157.