Title: A Case Study of Developing Mental Models Through Design

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The focus of most science classrooms is on teaching pieces of scientific knowledge rather than on teaching how the pieces of scientific knowledge are interconnected and fit together as a whole. It is no surprise U.S. students underperform in science achievement in comparison to other industrialized countries (TIMMS, 1999). Students have difficulty with scientific phenomena because scientific phenomena are taught as oversimplified collections of static facts and not as dynamic systems of interacting entities that change through time. In order to advance students' understanding of scientific systems from superficial to deep, students need to understand the functional relations and causal interactions between entities of the system, which involves having mental model representations.

Mental Models

Most cognitive theories about mental models concur that mental models consist of objects and their relationships (Johnson-Laird, 1983; Kearney and Kaplan, 1997; Jonassen, 1999). However, this definition is limited in that it does not address the greatest power of mental models: the ability to mentally simulate mechanisms to infer rules or make predictions about the operation of a system (Schwartz and Black, 1996; Koffijberg, 1996). From this mental-simulation perspective, a mental model is a dynamic mental structure whose behavior can be used to show how the systems modeled will function under different circumstances (Gentner and Stevens, 1983; Aronson, 1997). Thus, in the fullest sense, mental models consist of the structural components of the system, knowledge of the interrelatedness of those entities and a causal mechanism describing and predicting the performance of the system (Jonassen, 1999).

A mental representation that consists of entities and relationships of a system is not sufficient for understanding. There must be the capacity to reformulate or restructure the mental model and incorporate the consequences of this manipulation (Newton, 1996). This transformation or running of a mental model pertains to adjustments made through the application of the causal reciprocity found in the system. The definition of mental models for the purpose of this study involves the ability to visualize and reason about mechanisms by moving entities and seeing how they dynamically affect one another (Schwartz and Black, 1996). It is this act that allows the thinker to visually predict how or why a complex system works.

Design Activities

Engaging students in design activities can produce the intense involvement necessary for developing mental models. Research has shown that design activities engage students in making deep cognitive connections with the concepts that underlie the domain in which they are designing (Resnick & Ocko, 1990). Students are placed squarely in the process of constructing and using knowledge creatively. As designers, students determine the relevant entities and the interrelations among them. When this is established, the stage is set for reasoning about how the entities causally interact with each other as a united whole and the mechanisms that allow the entities to carry out their functions. Students can then run mental simulations of their systems and make predictions about how their systems might behave (de Kleer & Brown, 1983; Williams e al., 1983). Mental models of systems are developed as students attend to the systems' structural, functional and behavioral levels. The learning that ultimately results through designing is not only deeper, but also more meaningful.

Case Study

Reasoning about mechanisms facilitates a deeper level of understanding. It is *knowing why* a system work (Black, 1992) rather than *knowing that* it is a system. Getner (1983) suggested that people's scientific reasoning is influenced by their mental models. Thus, when students don't demonstrate mechanistic reasoning (Honey et al., 1991), they are not thinking beyond the superficial structural level. They don't understand the how and why behind scientific phenomena, which is a source of concern.

We conducted a case study to investigate the issue of reasoning about mechanisms at the middle school level. This age group of students was of particular interest to us because they were in the formal operations stage and therefore, developmentally ready for reasoning about mechanisms. We wanted to see to what extent middle school students would demonstrate this type of thinking during design. We also wanted to see if students were more likely to reason about mechanisms when asked to make predictions about how their systems might behave in a troubleshooting task. Finally, we were curious about gender differences in thinking and wondered whether they might be exhibited during these activities.

Method

Participants

The case study was carried out at a middle school in the South Bronx section of New York City. Twenty-three seventh grade students from a general science class participated in this study. There were ten boys and thirteen girls.

Procedure

We devised two different paper and pencil tasks. These two tasks were based on the Mars Millennium project (www.mars2030.org), which a number of organizations (e.g., NASA, NEH, etc.) were conducting to inspire students to be interested in Mars at the time when several space probes would be reaching the planet. The observations were divided into two days. Day 1 was the design task. Day 2 was the troubleshooting task.

Day 1 (Design Task)

On day 1 we asked the students to design a colony on Mars for a hundred people to live in the year 2030. The only constraint given was that the colony must be able to sustain the colonists for one full year. Before the students began creating their designs, the experimenters led the class in a group discussion about some information on Mars and Earth. This was a relatively brief discussion and only the salient facts of these two planets were mentioned. The goal was to provide students with adequate background information so as to ensure the integrity of their designs. In addition to the discussion on facts about Mars and Earth, the experimenters also led the class in a discussion about those aspects agreed upon by experts to be vital for the functioning and survival of a community. Thus, ten categories (e.g., air, water, food, shelter, transportation, communication, government, culture, health & safety, sanitation) were introduced and students were told to keep them in mind as they designed their communities. The students were given 30 minutes to complete this design task individually.

Day 2 (Trouble-shooting Task)

On day 2 the experimenters presented the students with the following hypothetical scenario: *The Mars colony is in trouble. A third of the colonists have become seriously ill. Your task is to determine possible cause(s) of this problem and explain why it happened.* Each student was provided with a packet containing a series of questions to answer. The students were also provided with their designs from day 1 to be used as references. The students had 30 minutes to complete this troubleshooting task individually.

Coding

Each participant received three scores. One score for *Entity*, one score for *Relationship*, and one score for *Mechanism*. These scores were measured according to the following coding system.

Entity: A point was given for every entity in a participant's design. An entity was determined to be a unit of any object. For example, if a participant had an oxygen tank and a building, he/she would receive a score of 2 for *Entity*.

Relationship: A point was given for every relationship specified between the entities in a participant's design. For example, if a participant had an oxygen tank connected to the side of a building, he/she would receive a score of 1 for *Relationship*.

Mechanism: A point was given for every dynamic functional relationship specified in a participant's design. For example, if a participant specified oxygen flowing into the building, he/she would receive a score of 1 for *Mechanism*.

Results and Discussion

Types of Thinking

Designing requires students to think about entities, the relationships among the entities and how the relationships contribute to the functioning of the whole system. Troubleshooting requires students to utilize their understanding of the dynamics of system to determine possible causes for a given problem. These tasks were used to stimulate more in-depth thinking about the operational mechanisms of systems. Unfortunately, the results obtained for the design and troubleshooting tasks did not reflect this intention (see Figures 1 and 2). There was a decreasing trend in points for each of the thinking types for both tasks. *Entity* received the most points ($M_{\text{Design}} = 4.22$, $SD_{\text{Design}} = 3.62$; $M_{\text{Troubleshooting}} = 2.65$, $SD_{\text{Troubleshooting}} = 1.99$), followed by *Relationship* ($M_{\text{Design}} = 1.27$, $SD_{\text{Design}} = 2.20$; $M_{\text{Troubleshooting}} = 1.30$, $SD_{\text{Troubleshooting}} = 1.29$) and finally *Mechanism* ($M_{\text{Design}} = .22$, $SD_{\text{Design}} = .63$; $M_{\text{Troubleshooting}} = .52$, $SD_{\text{Troubleshooting}} = .59$). Most students had simple units of objects in their designs. However, only a few students had meaningful connections between entities. Even fewer students had mechanisms in their designs. Without the prerequisite relationships, many students were unable to establish dynamic functional relationships. Thus, there were barely any mechanisms in their designs. One-Way ANOVA analyses and multiple comparison tests showed significant differences among the types of thinking in both the design task, $F(2,273) = 64.74$, $p < .001$, and troubleshooting task, $F(2,66) = 13.37$, $p < .001$.

Gender Differences

Studies have indicated that starting around adolescence, females as a group have learned mathematics less adequately than have males (Leder, 1992). These differences are seen most clearly in results of the Scholastic Aptitude Test (SAT) (Benbow & Stanley, 1980; National Science Foundation, 1994; Gallagher & DeLisi, 1994). Studies of adolescent students' perceptions of science and technology have indicated that significantly more females than males reported science courses were difficult to understand and computer courses were not interesting to learn (Daley, 1998; Jones, Howe, & Rua, 2000). Being able to conceptualize how complex systems work is often critical to scientific and mathematical analyses. Could the male advantage in math and science be the result of having better mechanism knowledge? There exists some evidence that females tend not to describe the internal mechanical parts of their designs (Brunner et al., 1990; Honey et al., 1991). These findings prompted an investigation of gender differences in types of thinking. For the design task a 3 (Thinking Type) x 2 (Gender) Factorial ANOVA was performed. There was a marginally significant main effect of gender, $F(1,270) = 3.67$, $p = .056$. A profile plot of points for *Entity*, *Relationship*, and *Mechanism* suggests that the significant main effect for gender might be at the *Relationship* stage (see Figure 3) because there is a dramatic drop in the girls' *Relationship* points. An independent *t*-test was performed for *Relationship* and it was found that the difference was indeed significant, $t(90) = 2.89$, $p = .005$. Although few students included relationships in their designs, those who did were boys. They significantly outperformed girls when it came to making relationships between entities. However, for the troubleshooting task, a 3(Thinking Type) x 2(Gender) Factorial ANOVA revealed no gender difference in types of thinking. Boys and girls performed similarly across the three types of thinking (see Figure 4).

Conclusion

It was clear from our case study that the middle school students weren't thinking at the mechanism stage. The results showed that student started thinking about relationships, but didn't fully complete this step. Without a firm understanding of relationships between entities the students could not progress to thinking about the dynamic functional relationships. Thus, there was very little evidence of mechanisms in the students' designs. This was true of both boys and girls. Although the findings on gender differences in types of thinking in our study were inconclusive, we recommend further investigation of this matter given the significant gender difference we found at the relationship stage in the design task, and also what we know about the male advantage in math and science subjects documented in gender research.

To help advance children's thinking beyond the entities stage, classroom instruction should focus more on the interrelations among the various levels of scientific systems. The relationships among entities serve as the glue that holds systems together. Without a clear understanding of how pieces of information are related and fit together as a whole, students are at a loss when it comes to mechanistic reasoning. We believe that a computer design program such as Inspiration can be an effective tool in teaching students about mechanisms that underlie systems. The program has ‘linking’ features that explicitly illustrate relationships among entities in systems and facilitate the designer’s reasoning about causal interactions and functional relations. The drawback in using Inspiration is that one can only create static designs; however, students will still receive a valuable learning experience because the concept of relationships is reinforced. By building diagrams of systems, students will be able to visualize how entities are related to each other through structure and function. Students’ understanding of dynamic functional relationships will gradually develop, which will set the stage for developing mental models. We hope to explore this method in future experimental research to examine its potential to improve children's understanding about relationships, and ultimately children’s understanding about mechanisms. On a broader scope, we hope to gain insight into the process of mental models reasoning, and inform the development of more directive science curricula that will encourage students to think on a deeper level.

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Figures

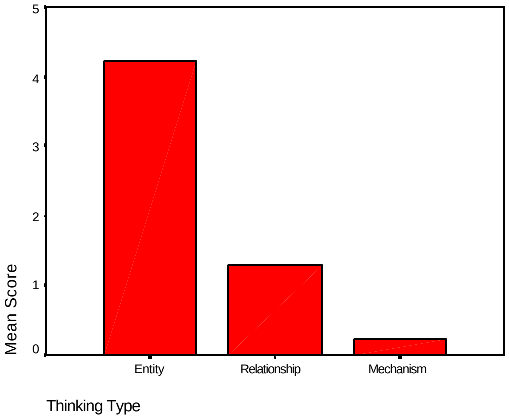

Figure 1. Mean Score for Thinking Types--Design Task

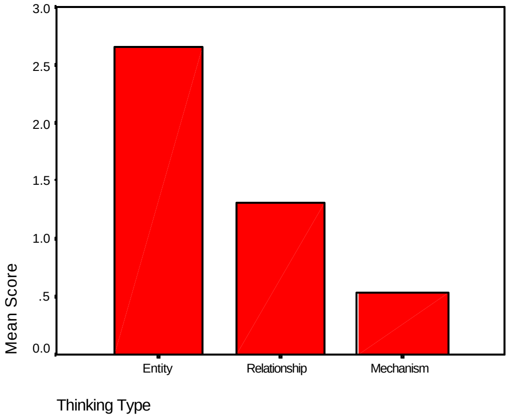

Figure 2. Mean Score for Thinking Types--Troubleshooting Task

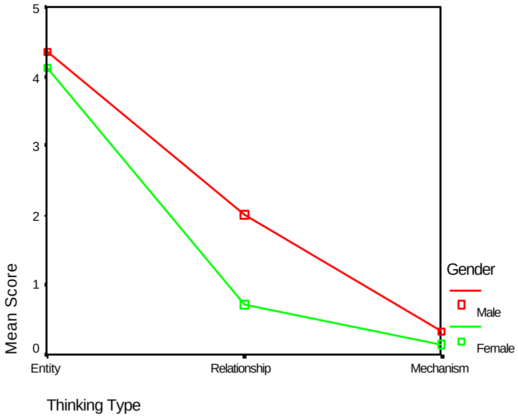

Figure 3. Mean Score in Relation to Gender for Thinking Types--Design Task

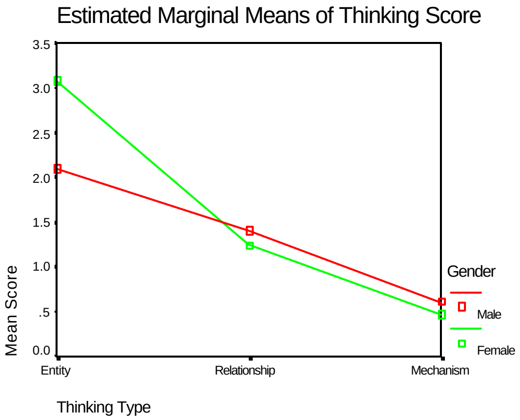

Figure 4. Mean Score in Relation to Gender for Thinking Types--Troubleshooting Task