Technology-Mediated Visualization and Interpretation of Chemical Phenomena by Middle School Students

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The use of models is a hallmark of scientific work and science education. Modeling tools give people the means to represent abstract concepts and complex phenomena in a more concrete and manageable fashion (Gilbert & Boulter, 1998). While expert scientists use modeling tools and modeling approaches, science learners can also benefit from modeling activity. Indeed current science education standards call for students in different grade levels to not only engage in modeling activities to help them understand scientific concepts, but also to gain an familiarity with modeling tools and activities to better understand scientific inquiry practices (National Research Council, 2000). Scientific models can be developed with a range of tools, ranging from simple drawings to mathematical formalisms to tangible physical representations. More recently, computer technology has allowed for more powerful modeling tools that utilize a range of multiple media and representations. As computers continue to increase in power and functionality, expert scientists and science learners can draw from these representations to develop models that would be difficult to develop with physical media. When we consider the range of modeling tools that are now available to science learners in today's classrooms, it is important that we understand how learners can best use those tools and what role different modeling tools and representations can play in an educational context.

For example, consider chemistry education, where it is important for students to represent and explain chemical phenomena at the molecular level. One traditional modeling tool used in chemistry education is the physical "ball and stick" model that allows students to build molecular representations. Computer-based modeling tools can also provide similar functionality, but as computer visualization capabilities become more powerful, students now have access to more dynamic types of representations. While physical tools can be useful to represent the static aspects of the molecular level (i.e., molecular structure), using them to represent the dynamic aspects of the molecular level (i.e., chemical reactions) may be more difficult. Computer tools, on the other hand, have the ability to provide the dynamic animation functionality that can help students model and think about these dynamic aspects. But while the roles for these different modeling tools may seem straightforward and intuitive, there is still a question about the utility of animated representations given their complexity and the actual differences between static and dynamic representations in this context.

In order to explore these issues, we developed *Chemation*, a modeling and animation tool for handheld Palm computers where students can view and build molecular animations. In the Chemation project, we are specifically exploring how dynamic representations might serve as an instructional aid for students who are working with complex dynamic processes and abstract representations in chemistry. In this presentation, we will discuss some current studies looking at the differences between student use of Chemation and physical models, and looking at different uses of Chemation in a middle-school science classroom context. By exploring these different issues, our goal is not necessarily to determine whether one type of representation is ultimately “better” than another. Rather, we hope to describe the pros and cons of the different representations in order to outline the roles that the different types of tools can play in a classroom setting.

The Use of Animation for Learning

There is an intuitive notion that animation can positively impact learning. However, while there is a body of work looking at how animation can be used for instructional purposes, there are still mixed results about the instructional value and effects of animation. For example, Mayer (2001) has looked at different combinations of animations and text to show which combinations can positively and negatively impact learning. However, Tversky, Morrison, & Betrancourt (2002) have described more mixed results of animation. While animations can help students visualize processes and construct mental models of those processes (Mayer & Moreno, 2002; Williamson & Abraham, 1995), there are still questions about the actual utility of animations in instructional settings. Often, animations are used to help learners view complex phenomena in different ways so they can develop a better understanding of that phenomena. For example, Weiss, Knowlton, and Morrison (2002) have discussed different functions of instructional animation that include:

- A decorative, cosmetic function that aims to make instructional material more attractive and motivating to learners.

- An attention gaining function to draw the learners attention to different aspects of instructional material.

- A presentation function where animation is used to present new concepts and procedures that may be difficult to understand due to their abstract, dynamic nature.

- A visual clarification function to provide conceptual understanding of ideas by accompanying instructional material that learners are currently working with.

When we consider instructional animation from these perspectives, we see that the role of animation as described is a more passive one where learners are simply viewing animated material. Certainly this viewing and presentation role can certainly be valuable, and there are many examples of such animated material. However, we are also interested in considering how animation can be used in a more active, constructivist manner. In other words, is there instructional value to having learners build animations and use them as artifacts to interpret and reason with? Additionally, we are interested in exploring how dynamic media like animation can compare with modeling tools that employ more static media, such as physical models. In order to explore these issues, we have performed two studies with Chemation looking at how middle school students use Chemation and physical models with a chemistry curriculum in a classroom setting.

Chemation Overview

Chemation allows students to build 2-D molecular "ball-and-stick" models and flipbook-style animations. Chemation contains five functional modes for students to create molecular models and "flipbook-style" molecule animations (Figure 1). Students can build molecules with an *atom palette* containing 21 different atoms that students can select from and place on the main screen. Sixteen of the atoms include symbols representing the frequently used elements (e.g., "H" represents hydrogen), while the remaining atoms are blank so that students can have them represent any element of their choosing. Students can select an atom from the palette and tap on the screen with their stylus to add the atom to the screen. Students use a *link tool* to connect atoms. In order to reduce the complexity of the tool, there is only the one link type—a straight line between atoms (note that the curricular activities that Chemation was initially developed to support does not yet deal with different chemical bonds). Students insert a link between two atoms by selecting the link tool from their tool bar and clicking on the two atoms that they wish to connect. Finally, students can also use a *text tool* to add small free form text labels to annotate their work. Sometimes students will add labels that identify their molecules, such as the water molecule label shown in Figure 1. Or students may add a label that describes some external action that is part of the phenomenon they are describing, such as by adding a label noting the addition of heat to the chemical reaction that they are representing in their animation.

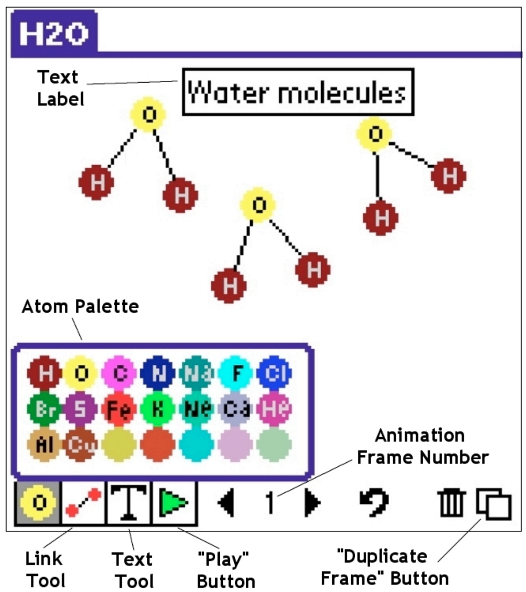

Figure 1. Chemation main screen

This illustrates how students can set up molecules and text on a single screen. Students can create animations by creating a series of individual screens (or frames) that Chemation can quickly flip through in rapid succession. Students begin an animation by setting up the first frame of their animation (Figure 1 shows the frame number of the animation). After students set up the items they want on the frame, they can press the "right arrow" adjacent to the frame number to move to the next frame. Students can then set up the components of the new frame with the Chemation tools, and repeat the process for as many frames as they want. Typically, students can set up a frame, use the "copy frame" command in Chemation, move to the next frame, paste the copied frame, and then make the desired changes in the new frame. Students continue with the process until they have created the desired series of frames. When the entire series is finished, students set the animation speed and press the "play" button on their toolbar to see the animation as Chemation steps through the frames at the specified speed.

Classroom Studies of Chemation

Given this brief overview of Chemation, we can now summarize two recent studies that explore Chemation use in middle-school science classrooms. One study involved a comparison between the use of Chemation and physical models. The second study focused on the use of Chemation for different animation construction, evaluation, and viewing activities.

Study 1: Comparing Chemation with Physical Models

The first study, which compared student use of Chemation to student use of physical ball-and-stick models, involved two teachers and 208 students in two Detroit public middle schools. The study was situated within chemistry lesson activities in a chemistry curriculum developed by our research group. The curriculum focuses on chemistry concepts including properties, substances and mixtures, chemical reactions, and conservation of mass. Each teacher in the study had some of their classes use physical models and their remaining classes use Chemation. Table 1 describes the number of students that were in each treatment group along with additional information about teacher experience with the given curriculum. The Chemation students were provided with Palm computers for the duration of the study. The physical models were the "gumdrop and toothpick" models that had been used before in those schools. Note that both teachers had been involved in previous activities with handheld computers, so the teachers and students were all familiar with Palms. Also, pretests showed no statistically significant differences between the students at the two schools in terms of prior chemistry expertise.

Teacher	Treatment 1: Physical Model Group	Treatment 2: Chemation Group
Teacher 1: Two years of experience with the curriculum	40 students	71 students
Teacher 2: New to the curriculum	33 students	64 students

Table 1. Number of students in each treatment for each teacher in Chemation study 1

Students built different models using their respective tools and they used these models for discussion throughout these curricular lessons. Table 2 provides an overview of the curricular lessons and the activities that the students engaged in. Students either used Chemation or gumdrop models for all the model-based activities in these four lessons. For dynamic processes like chemical reactions, Chemation students would build an animation, whereas physical model students would build models of the reaction starting point and manipulate the model to show how bonds break and atoms rearrange. In this study, we compared the Chemation students with the physical model students to see if there were any similarities and/or differences in the two groups with respect to how they built, interpreted, and reasoned with models.

Curricular Lessons	Student Activities
Lesson 5: "Why are the properties of a substance always the same?"	Students build models of two substances (water and urea) with their respective tools. Physical model students place models of each substance into separate bags to discuss substances, and models of both substances into a single bag to discuss mixtures. Chemation students draw separate for each substance to discuss substances and draw a single frame with both substances to discuss mixtures. All students discuss the differences between substances and mixtures.
Lesson 9: "Where did that green substance come from"?	Students use their respective tools to build models of copper atoms and acetic acid (vinegar). Students then use these models to demonstrate the process of a chemical reaction. Physical model students create models of the reactants and products, and manipulate these models to describe the reaction. Chemation students build animations that describe the chemical reaction.
Lesson 11: "What happens when I see different processes?"	Students interpret and discuss previously built models of molecular-level processes to identify each as a chemical reaction, mixing, or boiling. Physical model students refer to physical models and Chemation students refer to animations.
Lesson 14: "Why does mass stay the same in a chemical reaction?"	Students explore conservation of mass by building models of chemical reactions using their respective tools and examining what happens to atoms (and the number of atoms) during the reaction.

Table 2. Curricular lessons and the corresponding student activities for each lesson.

We collected different types of data to look at the different classes as a whole and to focus in more detail on the work by a subset of students. In terms of data collected from all of the students in the study, we collected:

- Videotaped records of the classes along with all the group activities where students used their respective modeling tools.

- Pre- and posttest data from all students, which included 12 multiple-choice and 3 open-ended questions assessing the chemistry concepts in the curricular lessons.

Additionally, in order to probe deeper beyond the pre/posttest data, we interviewed and observed a subset of 29 students (15 Chemation students and 14 physical model students).

These students were selected with input from the teacher in order to select a fairly even mix of high, medium, and low achieving students. For each of the four lessons, we developed interview questions that we later coded to probe these 29 students on the animations that they built and to have them use their animations to interpret or reason about a given chemical concept. The student interviews were coded using three ratings—proficient, basic, unsatisfactory—for both conceptual accuracy and thoroughness in students' responses. Finally, we interviewed the teachers to get their input on Chemation and examined the different artifacts that students created. The teacher interviews, classroom observations, and student artifacts were not coded and were used for reference.

Summary of Study 1: Similarities and Differences between Computer-based and Physical Modeling Tools

Overall, the pre- and posttest results for both the Chemation and physical model groups also showed significant gains of student content knowledge. The results of repeated measures ANOVA showed that student test scores increased significantly from the pre- to post-test [$F(1,204) = 784.075$, $p < .001$]. However, given the parameters of the study, we cannot isolate the tools as the contributing factor to these gains—the pre- and posttest results consider the overall learning environment, which includes the teacher supports, the tools, and other classroom materials. Indeed, the analysis showed that there was no significant interaction between total test scores and tool [$F(1,204) = .688$, $p = .408$].

However, as we looked closer at the student interviews throughout the study, we did see some similarities and interesting differences between the Chemation students and the physical model students in terms of the different chemistry content areas that were covered in the curricular activities. We are now attempting to articulate different dimensions of the two tools that may begin helping us explain our observations. Here, we will summarize the similarities and differences, and organize by these initial dimensions.

Core Representations

In terms of similar results, there were two areas with no major differences between the Chemation and physical model groups. First, in terms of dealing with 2-D model representations, most students in both groups demonstrated a basic conceptual accuracy of model representations. Second, in terms of chemical formula representations, all of the students in both groups indicated that a molecular model and corresponding chemical formula represented the same substance.

The similarities that we saw here may stem from the fact that each of these two content areas deals with the core molecular representation used by both Chemation and the physical models—a ball-and-stick representation. Neither of these content area deal with any dynamic or transformative aspects of chemistry. The first content area focuses on the core representation itself and the second content area focuses on the mapping between the core representation and the chemical formula representation. Since both Chemation and physical models both use the same core ball-and-stick representation, then essentially there is no difference between the tools with respect to these two content areas. Thus, it is not surprising that students from both groups had similar results on interview questions dealing with content areas focused on these representations.

Static vs. Dynamic Representations

We observed two differences between the students groups stemming from interview questions that were related to the more dynamic aspects of chemistry. The first difference between the student groups was that Chemation students had more thorough explanations than physical model students when describing atom rearrangement. Second, we saw that more Chemation students indicated that atoms did not rearrange during the mixing process than did physical model students. These interview questions fell in the "chemical reaction" content area because they were related to atom rearrangement. Because this content area has more dynamic characteristics, we feel that these results may be due to the differences between the static and dynamic representations offered by the two tools. Looking at these interview questions, it appears that the Chemation students had a better sense of atom rearrangement, both in understanding when and how atoms may rearrange. While this might make intuitive sense given the difficulty of representing atom rearrangement with a static model, we feel there may be two issues that arise here related to the difference between static and dynamic representations.

First, the fact that the Chemation students have to build animations may be giving them an advantage to help them understand atom rearrangement. Because the Chemation students had to engage in the animation building process, they had to think about different aspects of the phenomenon they are representing in their animation (i.e., atom rearrangement) in ways the that physical model students would not since they did not build any models to show dynamic aspects like atom rearrangement. Chang & Quintana (2006) note that the animation building process could help facilitate learning because learners have to use different cognitive strategies to do so, such as selecting and organizing content information for the animation and considering important characteristics of the process or phenomenon they are trying to describe. Therefore, the Chemation students may be at an advantage because the animation building process is essentially giving them an opportunity to reflect on dynamic phenomena that the physical model students lack.

Second, the fact that Chemation students had animations to refer to when discussing their answers to questions about atom rearrangement may have served as a support to help them focus and provide more thorough answers. Because animations represent a dynamic process, students were able to let the animation illustrate the actual atom rearrangement, letting them instead focus on chemistry content over descriptions of representational changes in their model. On the other hand, physical model students essentially had to deal with two different issues during their explanations because they used a single static model as the starting point for their discussion. As they describe chemistry concepts, they also have to verbally describe how the static model changes over time, i.e., describing which bonds might break, which atoms would rearrange, how they might rearrange, etc. In other words, the physical model students have to describe representational changes in their model (e.g., "this atom would break and move away") along with chemistry content. On the other hand, the Chemation students can focus on chemistry content because the animation itself is describing the representational changes. In this case, the dynamic model allows a measure of "offloading" to handle representational information, whereas the static model overloads students, forcing them to have to discuss content and representational information. This overloading may cause the students' content explanations to suffer.

Tangible vs. Intangible Representations

While we saw areas where Chemation students performed better than physical model students, we also saw the converse. Specifically, we observed two differences between the student groups on questions dealing with substances vs. mixtures and conservation of mass. The first difference was that more physical model students were able to explain the difference between substances and mixtures in terms of molecular constitution than Chemation students. Second, more physical model students described that atoms are conserved during a chemical reaction.

One explanation for these results could involve the tangible nature of the physical models versus the intangible nature of the computer models and the manner in which these models were used in the curricular activities for these content areas. In these activities, students acted on and manipulated the physical models in ways that they did not with the

Chemation models. For example, consider the curricular activities involved with substances and mixtures (Table 2). In these activities, students go beyond simply building molecular models (in this case, models of water and urea). The physical model students also collected the individual physical models that they built and placed them in separate bags: one bag for water molecules and one bag for urea molecules. These bags then represent the notion of substances because students discuss that each bag contains molecules of one type. Similarly, students placed models of water and urea molecules into a third bag, which denotes a mixture. Students go as far as to draw "sample mixtures" from the bag to note different characteristics of mixtures. Chemation students, on the other hand, do not engage in such tangible activities given the intangible nature of their computer models. The corresponding activities for Chemation students involve building separate frames to denote substances—one frame consisting only of water molecules and one frame consisting only of urea molecules. Chemation students then build a frame consisting of both types of molecules to denote a mixture.

While these activities may seem complementary in some respects, there may be an added benefit to the physical model students working with more tangible materials and representations to ground the material they are learning. The physical model students not only build molecular models, but they create concrete models of substances and mixtures. They also physically interact with those models by, for example, drawing sample mixtures of the bag to look at the results and note that mixtures are composed of different substances. On the other hand, the Chemation students only build models of the different molecules and models of a mixture and a substances, but they do not interact with those models in the same way that physical model students interact with theirs (e.g., they cannot "grab" sample mixtures from a Chemation frame).

In the second finding, we see a similar situation where students are exploring conservation of mass. The curricular activities for this content area involve building models of chemical reactions and then discussing what happens to the atoms during the reaction. Here, Chemation students build animations to describe the chemical reaction. However, the physical model students build physical models of the reactants, and then deconstruct and recombine those models to show how atoms form new products during the reaction. Students also note the number of atoms when they begin (i.e., the number of gumdrops) and see that the number of overall atoms must remain the same throughout the reaction. Since these activities focus on the atoms (and the number of atoms) throughout a reaction rather than the dynamics of the reaction (as seen in the previous section), the dynamic nature of the animation may not be as useful here. Furthermore, we made a second observation in the conservation of mass activities. Researcher and teacher observations noted that when building animations of a reaction that resulted in a lone atom (e.g., when the reaction produced a gas), some of the Chemation students would delete the lone atoms. In Chemation, it is very easy to delete an atom—a student simply draws a stroke through the atom with their stylus and the atom disappears. Therefore, it seems that some Chemation students were either neglecting to keep track of the number of atoms in their model, or thinking that a "leftover" atom was unnecessary, would delete the atom. This behavior was not seen in the physical model students, who may have felt that there were not supposed to destroy any of the atoms they were using (even if those atoms were merely gumdrops).

As we consider the potential utility of tangible representations, we can consider research on the how tangible materials and physical action can contribute to learning. Piaget (1954) and Bruner (1966) have long discussed the importance of concrete materials for child development and learning. Other work has shown how physical movement can enhance performance in spatially oriented tasks (Rieser, Garing, & Young, 1994) and how interaction with a physical environment can support the development of mathematic concepts, such as fractions (Martin & Schwartz, 2005). Thus in the case of the substance and mixture activities, the physical interactions with the bags and the handfuls of models may have helped ground and reinforce the notion of a substance and a mixture for the physical model students. Furthermore, in the case of the conservation of mass activities, the tangible nature of the static models and the procedure for modeling a reaction by deconstructing and reconstructing models in stepwise fashion may have helped students focus on conserving the number of atoms in their models. While students here are dealing with reactions, which are dynamic in nature, the focus of the activity is not on the dynamics of the process (as it was when students were showing and describing atom rearrangement), but rather on the number of atoms throughout a reaction. Therefore, the advantages of dynamic representations described earlier may not necessarily come into play here. In fact, if students are focusing more on atom rearrangement in order to develop an animated model of a reaction, students may be losing their focus on the true focus of the activity—conservation of mass (which may also explain why some Chemation students forget that they should not destroy atoms in their models).

Textually Augmented Representations

A final difference that we observed between the student groups was also in the "chemical reaction" content area, but this difference revolved around the manner in which students discussed their work. Specifically, more of the Chemation students used chemical names or formulas than did the physical model students. When interviewed about chemical reactions, Chemation students gave more thorough responses with more verbal descriptions that incorporated chemical names and details of the reaction. On the other hand, physical model students gave less thorough verbal descriptions, instead manipulating their physical model to try and demonstrate what is happening during a reaction with less usage of chemical names and other details about the reaction.

One reason that we may be seeing these patterns is that Chemation has more opportunities for textual augmentation than physical models. Here we use the term "augmentation" to mean instances where the tool can include text, either in the inherent design of the tool or via tool features that allow students to add text to their models. For example, Chemation include small textual cues through its use of labeled atoms in animations and in the atom palette. Furthermore, Chemation includes the label tool that allows students to annotate their animation in any way, either by including atom or molecule names, or by adding other descriptive text describing the reaction being modeled (e.g., noting some action that impacts the reaction, such as "heat is now being added"). The physical models lack easy textual augmentation, especially in the gumdrop models that students were using, which lacked the atomic symbols or an inherent ability to annotate the models.

The incorporation of text in Chemation thus may be important for two reasons. One, the element symbols may be giving students cues to support them in using more chemical names and descriptions. While these are abbreviated labels, they at least provide a cue that, coupled with the classroom activities, allow students to talk about different atoms using the atom name. Furthermore, the text tool gives students another means for articulation, allowing them to add more information about their models and modeling activity. Previous work has discussed the importance of supporting articulation in learner-centered software (Quintana, Reiser, Davis *et al.*, 2004). While the Chemation text tool is simple lacking other articulation prompts that can support students (Davis, 2003), the text tool could be used in conjunction with classroom activities so students can be more descriptive. While we need to continue with further analysis to see how students used the text tool, our initial observations coupled with the fact that Chemation has more built-in cues and opportunities for articulation than physical models may be one reason for these student differences.

Study 2: Exploring the Impacts of Different Animation-based Activities

A more recent study focused only on Chemation use. This study focused on the different ways that students could use animations to see if different combinations of these activities impacted student learning in any fashion. This study involved three teachers and 271 students in three Detroit public middle schools. The study was situated within the same chemistry curriculum as the first Chemation study. In this study, we looked at different student activities including: designing new animations (design), interpreting the animations (interpret), evaluating peer animations (evaluate), viewing and interpreting teacher-built animations (view). If we take a constructivist view, this study considered the potential impact of building animations. As discussed earlier, much of the previous work with animations has revolved around viewing and presentation activities. Here we also wanted to see how more active animation construction activities might impact learners.

Table 3 describes the number of students that were in each treatment group. For this study, all three teachers had three years of experience with the chemistry curriculum and Chemation. (Note that teacher 3 was reassigned during the study and thus lost the students in treatment 3.) As with the first study, there were no significant differences between the students in terms of prior chemistry experience. Students engaged in the curricular activities involved in lessons 5, 9, 14 described in Table 2. Students performed the activities that corresponded to their treatment group. For example, where students in treatments 1 and 2 would design animations as required by the curricular activities, students in treatment 3 would instead view teacher-built animations.

Teacher	Treatment 1: Design-Interpret-Evaluate Group	Treatment 2: Design-Interpret Group	Treatment 3: View-Interpret Group
Teacher 1	38 students	36 students	37 students
Teacher 2	31 students	32 students	37 students
Teacher 3	32 students	28 students	N/A

Table 3. Number of students in each treatment for each teacher in Chemation study 2

We collected different types of data similar to the data collection approach for study 1. The data included data collected from all students in the study and from a smaller focus group of selected students:

• Videotaped records of the classes, focusing on the six classes taught by teachers 1 and 2.

• Student background surveys for all students

• Pre- and posttest data from all students.

• Student artifacts developed by all students. Student artifacts included Chemation animations and worksheets that students worked on during their activities. Ten students from each treatment were randomly selected for focused artifact analysis to assess student content knowledge and skill with molecular representations.

• Post-instructional interviews of ten students from each treatment group to assess student content knowledge, molecular representation, and chemistry conceptual framework.

Summary of Study 2: Potential Impacts Between Multiple Activities with Computer-based Modeling Tools

Analysis for this study is still ongoing, but some initial observations do point towards advantages to the full set of modeling activities where students design, interpret, and evaluate animations. We can summarize some initial observations here:

• Students in treatments 1 and 2 developed a more coherent conceptual framework of the chemistry concepts they reviewed than did students in treatment 3. More than half of the students in treatments 1 and 2 were able to connect between a molecular representation and a corresponding macroscopic phenomenon or to use a molecular view to discuss chemistry concepts.

• More students in treatment 3 (80%) developed fragmented conceptual framework than students in treatments 1 (10%) and 2 (30%). These students had difficulty in connecting molecular explanations to a corresponding macroscopic phenomenon or to use a molecular view to discuss chemistry concepts.

• Most of the animations created by students in treatment 1 (80%) showed completely accurate chemistry content compared to only 23% of the animations in treatment 2. This seems to indicate that evaluating peer models can help students further develop content knowledge shown in their animation and generate higher quality molecular visualizations.

- More of the animations from treatment 1 (83%) incorporated textual representations in the models compared to 20% of the animations from treatment 2. This seems to indicate that the peer evaluations led students to improve their own models through the use of textual annotations.

While there are more results forthcoming from this study, it does appear that the animation construction process is having a positive impact on students in terms of their understanding of the chemistry concepts and activities in the curriculum. The students that simply viewed animations did not develop the stronger conceptual frameworks that other students did, Rather than using animation as a presentation tool to convey content information to learners, animation can be used in a more active, constructive manner. Furthermore, it seems that peer evaluation was also a useful activity for students. The students that engaged in peer evaluation of animations developed richer models and showed a stronger grasp on the relevant chemistry concepts than the students that did not evaluation peer models.

Concluding Remarks

Learning contexts such as classrooms are complex systems that incorporate, among other things, a range of instructional activities and support along with tools and other resource. As we create new tools, it is important to consider how those tools fit the context and to what extent they support the instruction in that context. As we said at the outset, our goal in the Chemation project is not necessarily to show that a computer-based animation tool is superior to other types of tools. Rather, we want to articulate the pros and cons of different tools to show the instructional instances where the tool can be useful and how different tools can complement each other.

Our work thus far has investigated how middle school students use Chemation as part of a chemistry curriculum. We have looked at student use of Chemation as compared to student use of physical models, and the different ways that Chemation can be used in order to outline the instances when Chemation seems to provide more (and less) utility to students in curricular activities. Such an analysis is necessary because there is no “one size fits all” tool or representation—different tools provide learners with different representations, some of which are more suited to certain types of instructional activities and the thinking necessary to engage in those activities. For example, we have discussed how the dynamic animation capability in Chemation can be more advantageous than static representation in physical models when learners have to think about the dynamic aspects of chemistry. However, the tangible nature of physical models may offer advantages by allowing students to explore certain chemistry concepts in a more interactive manner than they can with the virtual representations provided by a computer tool. Furthermore, our Chemation work has also begun to show the value of building animations in addition to the more typical information presentation role of animation, which may analogous to other model building activities that play an important role in science education. If we consider a constructivist perspective, our current work suggests that a combination of model building, model interpretation, and peer model evaluation can be a powerful combination to support learning. Indeed, Chemation serves as an example of a tool that can facilitate learning by supporting activities where learners construct, reflect on, and explain content-related artifacts.

Additionally, aside from describing the roles that different tools can play in an instructional context, we also feel that our work can also shed some light on the instructional activities themselves. Certainly there are activities that may be more suited to a given tool. For example, we saw where using static models to describe dynamic processes can be difficult since students have to deal with explaining both the dynamics being modeled and the phenomenon represented by the model. However, perhaps such an instructional activity could be modified so that students create a series of static models, each at a different step in the dynamic process. This way, students could have intermediate representations that can help them offload some of the underlying dynamics to the static *series* of models. As another example, we saw the potential value of textual augmentations in a computer-based model. Perhaps this can also lead to modified instructional activities that have learners label their static models or to emphasize the use of domain terminology more often when using models that do not have inherent textual tools. Finally, as we explore different types of tools, we can also consider the development of a new generation of "digital manipulatives"—physical tools that also augment computer function to blend different advantages from physical and computer-based tools (Resnick, Martin, Berg *et al.*, 1998).

Our work is not yet final and we are still analyzing data from our studies. But as we now work to develop explanations for our classroom observations, we feel that we can begin proposing different dimensions to help us articulate how different types of tools can offer different types of support for instruction. Outlining the roles that different tools can play is important. As Cohen, Raudenbush, and Ball (2003) note, we should avoid a characterization where we say that resources in an instructional context (such as technology tools) lead to learning. It is instruction that leads to learning and the resources in the context support this instruction. Only by carefully studying and understanding the affordances of different tools can we outline how these tools support instruction (and how that instruction might be enhanced). We hope to continue adding to this knowledge base as we explore the media and representations that tools like Chemation and provide to learners.

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References

Bruner, J. (1966). *Towards a theory of instruction*. New York: W.W. Norton.

Chang, H., & Quintana, C. (2006). Student-generated animations: Supporting middle school students' visualization, interpretation, and reasoning of chemical phenomena, *Proceedings of the 7th International Conference of the Learning Sciences*. Bloomington, IN: Lawrence Erlbaum Associates.

Cohen, D. K., Raudenbush, S. W., & Ball, D. L. (2003). Resources, instruction, and research. *Educational Evaluation and Policy Analysis*, *25*(2), 119-142.

Davis, E. A. (2003). Prompting middle school science students for productive reflection: Generic and directed prompts. *Journal of the Learning Sciences*, *12*(1), 91-142.

Gilbert, J. K., & Boulter, C. J. (1998). Learning science through models and modelling. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (Vol. 1, pp. 53-66). Hingham, MA: Kluwer Academic Publishers.

Martin, T., & Schwartz, D. L. (2005). Physically distributed learning: Adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive Science*, *29*, 587-625.

Mayer, R. E. (2001). *Multimedia learning*: Cambridge University Press.

Mayer, R. E., & Moreno, R. (2002). Animation as an aid to multimedia learning. *Educational Psychology Review*, *14*(1), 87-99.

National Research Council. (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. Washington, D.C.: National Academy Press.

Piaget, J. (1954). *The construction of reality in the child*: Basic Books.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., et al. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences*, *13*(3), 337-386.

Resnick, M., Martin, F., Berg, R., Borovoy, R., Colella, V., Kramer, K., et al. (1998). Digital manipulatives: New toys to think with, *Human Factors in Computing Systems: CHI 98 Conference Proceedings*. Los Angeles, CA: Addison-Wesley.

Rieser, J. J., Garing, A. E., & Young, M. F. (1994). Imagery, action, and young children's spatial orientation: It's not being there that counts, it's what one has in mind. *Child Development*, *65*(5), 1262-1278.

Tversky, B., Morrison, J. B., & Betrancourt, M. (2002). Animation: Can it facilitate? *International Journal of Human-Computer Studies*, *57*, 247-262.

Weiss, R. E., Knowlton, D. S., & Morrison, G. R. (2002). Principles for using animation in computer-based instruction: Theoretical heuristics for effective design. *Computers in Human Behavior*, *18*, 465-477.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching*, *32*(5), 521-534.