

The Impact of Designing and Evaluating Molecular Animations on How Well Middle School Students Understand the Particulate Nature of Matter

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ABSTRACT: In this study, we investigated whether the understanding of the particulate nature of matter by students was improved by allowing them to design and evaluate molecular animations of chemical phenomena. We developed Chemation, a learner-centered animation tool, to allow seventh-grade students to construct flipbook-like simple animations to show molecular models and dynamic processes. Eight classes comprising 271 students were randomly assigned to three treatments in which students used Chemation to (1) design, interpret, and evaluate animations, (2) only design and interpret animations, or (3) only view and interpret teacher-made animations. We employed 2-factor analysis of covariance and calculated effect sizes to examine the impact of the three treatments on student posttest performances and on student-generated animations and interpretations during class. We used the pretest data as a covariate to reduce a potential bias related to students' prior knowledge on their learning outcomes. The results indicate that designing animations coupled with peer evaluation is effective at improving student learning with instructional animation. On the other hand, the efficacy of allowing students to only design animations without peer evaluation is questionable compared with allowing students to view animations. © 2009 Wiley Periodicals, Inc. *Sci Ed* **94**:73–94, 2010

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INTRODUCTION

The National Science Education Standards (National Research Council, 1996) recommend that chemistry concepts such as substances, chemical properties, and chemical reactions comprise core learning content for fifth to eighth graders. However, learning these concepts without reference to the particulate nature of matter requires little robust understanding and can cause learning difficulties. For example, observations of macroscopic phenomena such as a change in color or the generation of gas products reveal little about whether the phenomenon involves a chemical or physical change. The explanatory power of chemistry is at the molecular or atomic level (Hesse & Anderson, 1992; Treagust & Chittleborough, 2001), and researchers have suggested that instruction focusing on the molecular level would help students develop adequate understanding of chemistry concepts and principles (Ahtee & Varjola, 1998; Driver, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Gabel, 1993).

The abstract nature of atoms and molecules can cause learning difficulties, which can be ameliorated by using models to improve the understanding of the particulate nature of matter (Appling & Peake, 2004; Gabel, 1993; Gabel & Sherwood, 1980; Rotbain, Marbach-Ad, & Stavy, 2006; Sanger, 2000). Although physical models have traditionally been used in science classrooms, educators can now use a range of computer-based models that employ advanced visualization and animation techniques. In particular, dynamic computer-based models or animations can help students visualize the molecular process of a chemical phenomenon that might otherwise be difficult to depict.

However, studies have indicated that animations alone might not be sufficient to improve student understanding (Hubscher-Younger & Narayanan, 2003; Rieber, 1990) and different instructional methods employing animations to promote understanding have been considered (Mayer & Anderson, 1992; Mayer & Moreno, 2002; Vermaat, Kramers-Pals, & Schank, 2003). In the present study, we explored the use of different activities mediated by an animation tool to promote the understanding of chemistry by middle school students. The animation tool used in this study, Chemation, runs on handheld Palm computers for portability and pervasive access of student artifacts and allows students to build two-dimensional (2-D) models and flipbook-style animations of chemical phenomena at the molecular level (Chang, Scott, Quintana, & Krajcik, 2004). In addition, the infrared interconnectivity of Palm computers allows students to easily exchange animations for peer evaluation or discussion. This study investigated whether allowing students to design and evaluate their animations of molecular processes helps them learn the particulate nature of matter and related chemistry concepts.

We employed three treatments in which students used Chemation to (1) design, interpret, and evaluate animations, (2) only design and interpret animations, or (3) only view and interpret teacher-made animations. This design includes one group with a complete combination of the designing, interpreting, and evaluating activities (the first treatment, T1) and two groups involved in part of the activities (the second and third treatments, T2 and T3). T1 and T2 were compared to detect the impact of evaluating student-generated animations, and T2 and T3 were compared to detect the impact of having students design animations. The results of this study provide insight into how best to use instructional animations to promote successful learning.

OUR PREDICTIONS

We predicted that the developed understanding of chemistry would be better for T1 students (who participated in the complete sequence of the modeling activities that included

designing, interpreting, and evaluating dynamic molecular models) than for T2 students (who participated in only designing and interpreting dynamic molecular models, without peer evaluation). Peer evaluation can help student assessors reflect on a series of criteria that indicate the good quality of the artifact involved in the learning task and later apply those criteria to their own task (Linn & Eylon, 2006; White & Frederiksen, 1998, 2000). Research shows that peer evaluation such as reflective assessment helps students improve the quality of their artifacts (White & Frederiksen, 1998, 2000) and the scores of younger and lower achieving students in achievement tests (White & Frederiksen, 1998, 2000). Moreover, peer evaluation allows students to understand that their models or artifacts need to be evaluated and improved toward valid scientific models (Schwarz & White, 2005). However, a time effect could confound the results of this study since the instructional time was longer for T1 than for T2. This time effect was reduced by the teachers in this study spending approximately the same amount of time on the lessons for each treatment by having T2 and T3 students work on reading material, summarizing the concepts taught in the lessons for the balance of the time available.

We were uncertain what the comparison between T2 and T3 would reveal. In our case study of student learning with Chemation, we found that allowing students to design a series of dynamic molecular models prompted them to think about the intermediate process in a chemical reaction, which facilitated the interpretation and reasoning of chemical phenomena at the molecular level (Chang & Quintana, 2006). Wu and Krajcik (2006) also showed that creating models provides students with opportunities to engage in thoughtful discussions on inquiry processes and scientific concepts. However, having students merely view animations created by others could be similarly effective if such animations are not too complex for the students and if this is combined with activities that engage students in active learning. The viewing approach might even have a stronger effect if the interactivity in the design process cognitively overloaded the students (Chandler, 2004; Moreno & Valdez, 2005).

THEORETICAL AND EMPIRICAL BACKGROUND

The Difficulty of Understanding the Particulate Nature of Matter

Students often confuse a physical change, such as phase change, with a chemical change (Ahtee & Varjola, 1998; Stavridou & Solomonidou, 1998). For example, interviews with 40 students (from 12 to 18 years old) about their conceptions of chemical reactions found that younger students tended to give definitions of chemical reaction as the phenomenology of change and were unable to distinguish between different types of change, such as physical and chemical ones. The older students (five 18-year-old students) who had attended more chemistry courses were better able to explain a chemical reaction at the molecular level, but they were still unable to connect this explanation with the chemical phenomenon (Stavridou & Solomonidou, 1998). These authors found that students often find it difficult to connect between molecular explanations and visible phenomena.

Other studies have similarly found that few students tend to use atomic or molecular explanations for chemical phenomena (Abraham, Williamson, & Westbrook, 1994; Hesse & Anderson, 1992). Moreover, students might demonstrate a connected but alternative understanding of a scientific phenomenon at the macroscopic and molecular levels. For example, Chiu, Chou, and Liu (2002) found that two thirds of thirty 10th-grade students showed difficulty differentiating between macroscopic and molecular viewpoints. The students considered that mixing two solutions of different colors was the same as mixing two paints of different colors together and hence predicted that when the particles of a blue solution mixed with the particles of a red solution, the particles would turn purple.

Middle school students experience fundamental difficulties understanding the molecular constitution of substances (Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993), with many of them never having heard of molecules. Some such students consider that molecules are *in* substances, rather than that substances consist of molecules, and believe something to be between the molecules. Osborne and Cosgrove (1983) found that 8–17-year-old students in New Zealand knew little about the particulate nature of matter. With little knowledge or an alternative understanding about the particulate nature of matter, students might not understand that a chemical equation represents a chemical reaction involving atom rearrangement and bond breaking and formation (Krajcik, 1991).

To develop an in-depth understanding of the particulate nature of matter, students need to possess related scientific knowledge such as the molecular constitution of a given substance (Abraham, Grzybowski, Renner, & Marek, 1992; Nakhleh, 1992; Nakhleh, Samarapungavan, & Saglam, 2005). Equally important, students need to master certain abilities and skills such as visualizing a chemical reaction at the molecular level, reasoning about a macroscopic phenomenon using chemical representations, and coordinating multiple representations (Ben-Zvi, Eylon, & Silberstein, 1987; Gabel & Samuel, 1987; Hesse & Anderson, 1992; Kozma, 2000, 2003; Krajcik, 1991; Yaroch, 1985). Finally, students need to develop a coherent conceptual framework that integrates their knowledge and skills to establish a scientific theory of the entities and processes that underlie a given observed phenomenon (Kozma, Russell, Jones, Marx, & Davis, 1996; Russell et al., 1997). For example, although Nakhleh et al. (2005) found that more than half of the nine middle school students they interviewed had some understanding of the particulate nature of matter, their conceptual framework was rather fragmented. In the present study, we examined these aspects of students' understanding of chemistry to determine the effectiveness of an animation tool coupled with students performing the following four types of modeling activities: designing, viewing, interpreting, and evaluating dynamic molecular models of chemical phenomena.

Using Models to Support Students in Learning Chemistry

External models can mediate the formation or elaboration of students' mental models of a particular concept or phenomenon. External models shape or give rise to students' mental models and students' preexisting mental models influence their perception of phenomena and understanding of external models (Buckley, 2000; Buckley & Boulter, 2000; Rohr & Reimann, 1998). For example, a case study by Rohr and Reimann (1998) revealed that students' beliefs, perceptions of phenomena, and explanations of external representations interact and coevolve over the course of learning with multiple representations.

Models can be displayed with different media, including 2-D drawings on paper, three-dimensional (3-D) manipulative models constructed from physical objects, and 2-D or 3-D models presented on a computer display. Computer-based technology is playing an increasing role in supporting teaching and learning activities, utilizing the dynamic, interactive, and multimodal capabilities of computer displays. Encouraging results have been reported for the various computer-based modeling programs that have been developed to improve student learning of chemistry (Ardac & Akaygun, 2004; Barnea & Dori, 1996; Kozma et al., 1996; Schank & Kozma, 2002; Wu, Krajcik, & Soloway, 2001). For example, Kozma et al. (1996) incorporated multiple representations into the program MultiMedia and Mental Models (4M: Chem) to support the understanding of chemical equilibrium by college students. They found that this increased students' understanding of equilibrium

and reduced the number of misconceptions. Wu et al. (2001) investigated how 11th-grade students developed their understanding of chemical representations with the support of an interactive program called eChem that allowed students to build and manipulate 3-D molecular models and view multiple representations simultaneously on a computer. They found that eChem features helped the students construct models and translate representations. Another program, ChemSense, allows students to construct and discuss chemical representations in a virtual space on the computer (Schank & Kozma, 2002). Schank and Kozma (2002) found positive correlations between the numbers of drawings created in ChemSense and students' representational competence and between the numbers of drawings and their quality. Molecular Workbench is another computer program with highly interactive features to support students in developing visualizations of molecular or atomic concepts (Tinker, n.d.). This program allows students to change the parameters of a visual display to develop and test their ideas, theories, and hypotheses.

Although technology tools exist for students who are learning chemistry concepts and principles, we need another tool that makes the concept of the particulate nature of matter accessible to middle school students. Computer programs that include complex chemistry concepts such as the dynamic aspect of chemical equilibrium, 3-D structures of molecules, or different types of bonds could impede the learning of younger students. We therefore developed a simple program, Chemation, to address the learning goals of a seventh-grade, inquiry-based chemistry curriculum (Chang et al., 2004). Chemation runs on a handheld device, which is cheaper than a desktop computer and has the significant advantage of portability (Soloway et al., 1999). Because of their one-on-one nature, handheld computers encourage continual, individual work that increases students' ownership of their artifacts. The portability and ease of access of handheld computers enable students to use the animation program in the same physical space and at the same time as the teaching and learning activities (Roschelle, 2003).

Issues of Using Models and Modeling to Support Science Learning

Although allowing students to learn science with models appears promising and beneficial, this might also introduce extra learning difficulties. First of all, the knowledge, experience, and ability of students to perform a technology-mediated modeling activity are limited compared with those of scientists. For example, a study examining representational competencies of professional chemists and college students revealed that chemists are fluent in transforming between multiple representations when contemplating the same phenomenon, whereas student thinking is constrained by the features of a particular representation (Kozma, 2003, n.d.). Moreover, chemists use representations to help them think and reason about the conditions and mechanisms underlying experimental observations, whereas students building molecular models in a computer laboratory rarely connect with such observations (Kozma, 2003, n.d.).

Schwarz and White (2005) investigated four classes of seventh-grade students in the Model-Enhanced ThinkerTools (METT) inquiry curriculum, in which students created and tested their own models of force and motion, evaluated the models of their peers, and reflected on the nature of models. The results of that study indicated that these explicit modeling activities improved students' metamodeling knowledge, that is, knowledge of the nature and purpose of scientific models. However, Schwarz and White found that the overall scores of inquiry skills and physics knowledge did not differ significantly between students who used the METT and those who used ThinkerTools in the original curriculum in

which the modeling activity was not emphasized. These authors considered that the results were inconclusive regarding the impact of the modeling activities on students' conceptual understandings and modeling abilities.

In this study, we investigated the impact of using the Chemation animation tool when students were performing four types of modeling activities: designing, viewing, interpreting, and evaluating dynamic molecular models of chemical phenomena. Each of these animation-based modeling activities involves a different approach to the use of instructional animation. As indicated above, we were particularly interested in whether the activities of designing and evaluating dynamic molecular models add any educational value to the approach of viewing animations in terms of enhancing the understanding of chemistry by students.

THE ANIMATION TOOL: CHEMATION

Chemation is a program on Palm computers that allows middle school students to build 2-D molecular models and flipbook-style animations (Chang et al., 2004; Chang & Quintana, 2006). Chemation contains the following five modes (Figure 1): (1) *Atom mode*: The atom palette contains 21 different atoms that students can choose and drag to the main screen. (2) *Link mode*: The link mode is used to connect between atoms. (3) *Molecule mode*: Once atoms are drawn and connected, they are viewed as a group of atoms in a molecule. Students can use the molecule mode to copy, paste, rotate, and flip the complete molecule. (4) *Label mode*: Labels are free-form text boxes that allow students to document their model. (5) *Animation mode*: After building molecular models, students can develop a series of frames to animate the models to articulate the details of a chemical or physical process (Figure 2).

Six types of support are provided by Chemation (see Table 1; Chang & Quintana, 2006): (1) Content-specific support to help learners build appropriate animations, such as the simplified atom palette, element symbols, and real-time messages for invalid atom connections; (2) construction support to help learners build animations efficiently, such as the copy tool for information transfer and undo/redo tool for revision; (3) multiple representations to

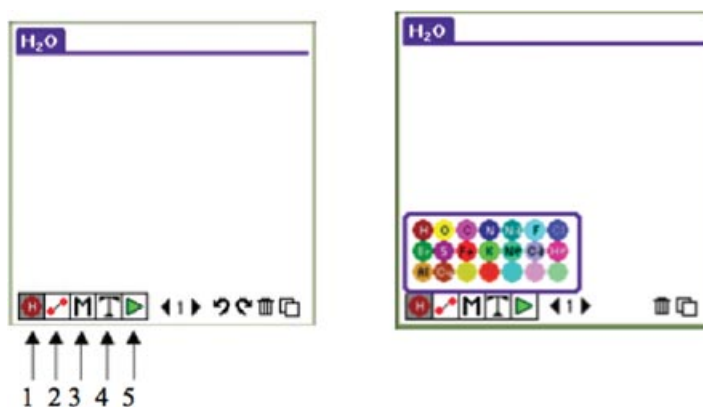


Figure 1. Five modes and the atom palette of Chemation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

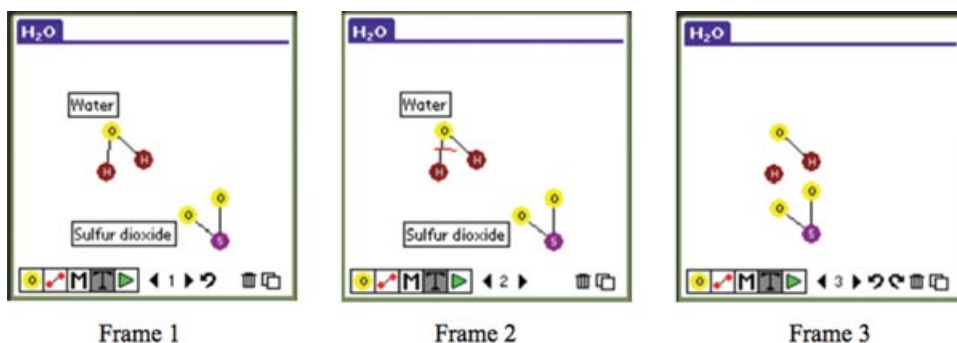


Figure 2. An example of animating a chemical reaction. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 1
Supports From Chemation

Student Activity Related to the Use of Animation		
1. Visualization of a chemical process	2. Interpretation of a chemical process	3. Reasoning about a chemical phenomenon
(1) Content-specific supports to help learners build appropriate animations: <ul style="list-style-type: none"> • Simplified atom palette • Element symbols • Real-time messages for invalid atom connections • Simplified link tool (2) Construction supports to help learners build animations efficiently: <ul style="list-style-type: none"> • Copy tool for information transfer • Undo/redo tool for revision • Nonlinear tool bar for multiple paths of revising 	(3) Multiple representations to support multimodal articulation: <ul style="list-style-type: none"> • Graphic interface for building visual (nontextual) representations • Labeling tool for inserting textual description (4) Multiple paths of navigation to support different spatial and temporal needs of viewing: <ul style="list-style-type: none"> • Frame-by-frame navigation • Continuous playing • Navigation to a particular frame 	(5) Manipulation tools to support atom/molecule rearrangement and movement: <ul style="list-style-type: none"> • Deletion function to remove connections between atoms for atom rearrangement • Dragging function to move atoms or molecules (6) Sustained artifacts to support ongoing reasoning: <ul style="list-style-type: none"> • Real-time save function for preserving students' working processes

support multimodal articulation, such as the graphic interface for building visual (nontextual) representations and the labeling tool for inserting textual descriptions; (4) multiple paths of navigation to support different spatial and temporal interpretation methods, such as frame-by-frame navigation and navigation to a particular frame; (5) manipulation tools to support atom/molecule rearrangement and movement, such as the functions of deleting and dragging; and (6) sustained artifacts to support ongoing reasoning, such as a real-time save function for preserving the working processes of the learner.

TABLE 2
Numbers of Students From Each Teacher in Each Treatment

	Treatment		
	T1	T2	T3
Teacher A	38	36	37
Teacher B	31	32	37
Teacher C	32	28	N/A
Total	101	96	74

Note. T1 = the first treatment (design, interpret, and evaluate); T2 = the second treatment (design and interpret); T3 = the third treatment (view and interpret).

METHODS

Participants and Study Design

The study involved three teachers and their 271 seventh-grade students in eight classes at three public middle schools in the Midwest (Table 2). The teachers had at least 3 years of experience with Chemation and the inquiry-based chemistry curriculum with which the activities of using Chemation were aligned. Originally, each teacher had three seventh-grade classes participating in the study. Each class was randomly assigned to receive one of the treatments so that each teacher taught all three treatments. The purpose of this restricted random assignment was to reduce the potential confounding effect of instructional methods. However, after the school year started, Teacher C lost one of her seventh-grade classes (the third treatment) because of a change of assignment to teach eighth-grade science.

In addition, the third treatment (T3, view and interpret) by Teacher B involved students with better mathematical ability (as selected by the school). However, the students in the three treatments provided by Teacher B had comparable prior knowledge of chemistry, as indicated by there being no significant difference in their pretest scores [$F(2, 67) = 0.828$, $p = .441$]. Most of the students at the three public middle schools were from ethnical minorities: 86% of Teacher A's students were African American students, 54% of the students in Teacher B's classes were Hispanic students, and 54% of the students in Teacher C's classes were African American students. All students were Palm-literate when they started the chemistry unit since they had used Palm computers in a previous inquiry-based air quality unit.

Materials

We developed learning materials, pre- and postinstructional chemistry achievement tests, and postinstructional interview questions. In this paper, we focus on student responses to the learning materials and pre- and posttests.

Learning Materials to Guide Modeling Activities. Chemation was used in three lessons of a seventh-grade inquiry-based chemistry curriculum entitled "How can I make new stuff from old stuff?" (McNeill et al., 2003). In addition to providing the teachers and students with the chemistry curriculum material, we developed supplemental learning material to guide the modeling activities of the students in the three lessons in which Chemation was used: Lessons 5, 9, and 14. The material included prompting questions to guide the designing, viewing, interpreting, and evaluating activities of the students. Appendix A provides an example of the material used in Lesson 5 for T1. The T1 version of the learning material contained prompting questions for designing (including planning and constructing),

TABLE 3
Summary of the Animation-Based Modeling Activities

Activity	Description	Student Task
Design	Plan Think ahead about purposes or goals of constructing artifacts, generate ideas about steps to construct artifacts to meet the purposes, and identify objects to include in the artifact.	Students work in groups to: <ul style="list-style-type: none"> • Set goals for their animation by describing what they want to show with their animation, • Generate at least three steps to make the animation (break the task down into small pieces), and • Decide objects (circles, links) and numbers of objects needed in the animation.
	Construct Transform observation of a phenomenon into molecular representations.	Students work individually to: <ul style="list-style-type: none"> • Create 2-D molecular models, • Duplicate frames and make changes to form flipbook-style animations, and • Use text to label or describe the representation.
Interpret	Generate meanings from the representation and explain and reason about the phenomenon with molecular representations.	Students work in groups to: <ul style="list-style-type: none"> • Explain the meaning of their or teacher-made animation, • Relate to the macroscopic phenomenon the animation represents, and • Reason about the phenomenon using the animation.
Evaluate	Make comments to and judge the quality of students' own and each other's artifacts	Students work in groups to: <ul style="list-style-type: none"> • Determine the adequacy of the types and numbers of models in classmates' animation, • Compare the trajectory of movement in each other's animation, • Make suggestion to help improve the quality of the animation, and • Revise students' own animation

interpreting, and evaluating. Note that the evaluation criteria were not revealed to T1 students until the evaluation phase. However, the student experience in evaluation was supposed to help them revise their animation since T1 students were asked to revise their animation after evaluation. The evaluation experience in an earlier lesson could also have helped T1 students design other animations in later lessons since T1 comprised three iterations of designing, interpreting, and evaluating. The T2 version contained only the designing and interpreting parts without the evaluation criteria and other evaluation activities, and the T3 version contained only the interpreting part with the students instructed to view the teacher-made animations. Table 3 provides a summary of the student tasks in the modeling activities. The students used the same chemistry curriculum material in the other 11 lessons.

Pre- and Postinstructional Chemistry Achievement Tests. Items in the pre- and posttests were identical, including five multiple-choice, five mixed (in which the student

6. A chemical reaction occurs when a student combines carbon dioxide (CO₂) and water (H₂O).
- $$\text{CO}_2 + \text{H}_2\text{O} \rightarrow ?$$
- Using the principle of conservation of mass, which of the following could be the product of the reaction?
- H₂O₂ + CO₂
 - H₂CO₃
 - H₂O + CO₂
 - H₃CO₂
- Why could your chosen one be the product of the chemical reaction?
 - Why could not the others be the product?
 - Draw molecular models to represent this chemical reaction.

Figure 3. A mixed item in the pre–post test.

chooses an answer and explains why), and five open-ended questions. The multiple-choice items measured only content knowledge, whereas the mixed and open-ended items measured combinations of content knowledge and modeling abilities. For example, the following multiple-choice item measured the definition of a substance: A piece of copper is a substance because it (a) is made of the same type of atom throughout, (b) consists of many different types of atoms, (c) can be made into something different, or (d) reacts with other substances. For comparison, Figure 3 shows a mixed item, which measures the knowledge students have about a chemical reaction and conservation of mass and their ability to construct molecular models to represent the given chemical reaction. Figure 4 shows an open-ended question that measures their knowledge of phase changes and chemical reactions and their ability to evaluate the molecular models given in the question.

Overall, the measured content knowledge included chemical reactions, substances versus mixtures, conservation of mass, macroscopic versus molecular phenomena, and chemical representation. The measured modeling abilities included the construction, interpretation, and evaluation of molecular models by students. The items measuring knowledge and abilities corresponded to those taught in the three lessons.

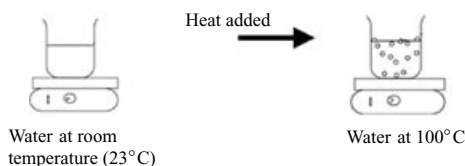
The assessment went through several rounds of revision. It was reviewed and edited by members of the science education faculty and a chemist at our university. All the items measured the content taught in the three lessons in which modeling activities with Chemation were implemented.

Procedure

The teachers and their students spent 10 weeks to complete the chemistry curriculum that contained 14 lessons. The curriculum engaged students in cycles of investigations that began with an exploration of macroscopic phenomena such as boiling, mixing, and chemical reactions and then guided students to use molecular models to explain the phenomena. Chemation was used in three lessons involving the teaching of molecular models. The activities of the three treatment groups differed only in the 3 lessons and remained the same in the other 11 lessons, since the teachers and students closely followed the curriculum and supplemental learning materials that we provided.

Each student was provided with a Palm computer for use in the three lessons. In Lesson 5, the students used Chemation to design, view, interpret, and/or evaluate (depending on the treatments) molecular models of water and urea and animations of the process of urea mixing into water. The learning goal for this lesson was for the students to understand that a substance is made of the same type of atom or molecule throughout, whereas a mixture contains multiple substances. In Lesson 9, the students again used Chemation to design,

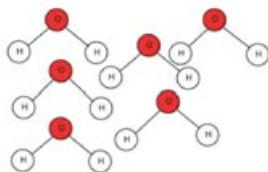
15. Susan observes that when boiling water (pure water), many bubbles come out of the water.



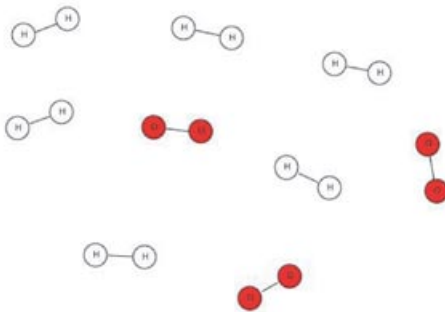
She makes drawings below to represent what happens to the molecules during the boiling process. Again your job is to evaluate Susan's drawing.

Susan writes and draws:

"Drawing 1: I draw models to represent molecules in the pure water at room temperature."



"Drawing 2: I draw models to represent molecules in the bubbles of gas when the pure water is at 100°C."



- (15.1) In Drawing 1, is there anything incorrect or inappropriate? Why are they incorrect or inappropriate?
- (15.2) In Drawing 2, is there anything incorrect or inappropriate? Why are they incorrect or inappropriate?

Figure 4. An open-ended item in the pre–post test. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

view, interpret, and/or evaluate animations showing the chemical reaction between copper and acetic acid at the molecular level to learn that atoms rearrange in a chemical reaction. In Lesson 14, the students for the third time designed, viewed, interpreted, and/or evaluated animations, this time of the chemical reaction between baking soda and hydrochloric acid. Students were guided to explain the principle of conservation of matter on the basis of an examination of the numbers and types of atoms present before and after the chemical reaction.

To ensure that the lesson time was the same for each treatment, the teachers had T3 students view two animations on the same concept in each lesson, and T1 and T2 students design only one animation about that given concept. It took 2–3 class periods to complete the entire modeling activities of T1 for each lesson but only 1.5–2 class periods to complete the modeling activities of T2 or T3. The teachers had T2 and T3 students work on reading material for the remainder of the time so that each treatment group had the same start and end dates for each lesson. Therefore, the total time spent on each lesson was the same for each treatment group. In other words, while T1 students were evaluating their animations, T2 and T3 students were reviewing the content knowledge learned in the lesson.

All the students took the pretest before beginning the curriculum and the posttest after finishing the curriculum. The tests required about two class periods to complete, which occurred over 2 consecutive days. After the posttest, the first author randomly selected 10 students from each treatment for interviews. A total of 30 students were interviewed. The interview results did not significantly differ from the other results reported in this paper and hence none of the interviews are described here in detail.

Data Coding and Analysis

Pre- and Postinstructional Chemistry Achievement Tests. The multiple-choice items were coded on the basis of their correctness, with 1 and 0 points given for correct and incorrect responses, respectively. For each subquestion of the mixed and open-ended items, 2, 1, and 0 points were given for completely accurate, partially accurate, and incomplete or inaccurate responses, respectively. The first author coded all the pre- and posttest data. In addition, we randomly sampled 10% of the pre- and posttest data and a second independent rater coded them. This produced an interrater reliability of 98.3% for the pre- and posttest data.

We included only those students who completed both pre- and posttests in the analysis. Because of high absenteeism in the urban schools, only 178 students took both tests. The numbers of students included in the analysis for each teacher and treatment are listed in Table 4. The missing data ($n = 93$) comprised 62 students who missed the pretest and 31 students who missed the posttest. In the missing data analysis, we focused on the latter 31 students to examine whether their absence in the posttest (but not in the pretest) introduced bias into the results. There were 12, 13, and 6 students in T1, T2, and T3, respectively, and their mean scores in the pretest did not differ significantly: 5.4 ($SD = 2.6$), 4.8 ($SD = 2.4$), and 6.8 ($SD = 3.7$) [$F(2, 28) = 1.022$, $p = .373$]. This indicates that the students missing

TABLE 4
Numbers of Students Included in the Analysis of Covariance

	Treatment		
	T1	T2	T3
Teacher A	24	30	21
Teacher B	16	18	26
Teacher C	24	19	N/A
Total	64	68	46

Note. T1 = the first treatment (design, interpret, and evaluate); T2 = the second treatment (design and interpret); T3 = the third treatment (view and interpret).

the posttest had homogeneous background knowledge of chemistry and hence it is unlikely that the results were influenced by the missing data.

We used two-factor analysis of covariance (ANCOVA) to examine the effects of different treatments on students' test scores with the treatment (design, interpret, and evaluate; design and interpret; or view and interpret) and teacher (A, B, or C) as the independent variables. The purpose of including the teacher as one independent variable was to detect any possible interaction between the teacher and the treatment. The posttest data were the dependent variable. We used the pretest data as a covariate to reduce the effect of student prior knowledge on the learning outcomes. An α level of .05 was used to test for significant effects and interactions. In addition to total test scores, we clustered the test items into items that measured (1) only content knowledge, (2) content knowledge and constructing ability, (3) content knowledge and interpreting ability, and (4) content knowledge and evaluating ability. We again used two-factor ANCOVA to examine the effect and interaction of treatment and teacher on the students' test scores in the four areas.

In addition to ANCOVA, we calculated effect sizes between T1 and T2 and between T2 and T3 with the difference between two means divided by the combined standard deviation for those means according to Cohen (1988).

Coding of Student-Generated Animations. We used three criteria to assess the quality of the animations generated by T1 and T2 students: accuracy, smoothness, and use of text. *Accuracy* refers to the level of content accuracy incorporated in the animation, *smoothness* refers to the number of frames created, and *use of text* refers to whether or not textual representations were included appropriately. A general coding scheme is given in Table 5, from which we developed specific coding schemes that indicated, for example, a complete list of accurate components needed to be included in the animation for different lessons. In general, for each criterion, a score of 2 was given for a satisfactory

TABLE 5
A General Coding Scheme for Student-Generated Animations

	Accuracy of Content	Smoothness (Measured by Number of Frames)	Use of Text
Proficient (2)	Student's animation includes all accurate components	Number of frames ≥ 15	Use text to accurately describe models or processes
Satisfactory (1)	Student's animation includes part of the accurate components or all components with minor errors	$3 \leq$ Number of frames < 15	Use text but with minor errors
Unsatisfactory (0)	Student's animation includes none of the accurate components or based on personal preferences	Number of frames < 3	No text used or text used invalidly

response, 1 for a satisfactory response but with minor errors, and 0 for an unsatisfactory response.

Coding of Student Interpretation of Animations. In the interpreting activity, students were guided to write down their interpretation of the animation and connection to the macroscopic phenomenon. We used three criteria to examine the quality of their written interpretations: (1) *accuracy of content*, which refers to the accuracy of the content incorporated in the interpretation; (2) *thoroughness*, which refers to the detail of the discussion of atom rearrangement; and (3) *coherence*, which refers to the coherence between the animation and interpretation of the student. Again a score of 2 was given for a satisfactory response, 1 for a satisfactory response but with minor errors, and 0 for an unsatisfactory response.

RESULTS

Student Performance on the Pre- and Postinstructional Chemistry Achievement Tests

The ANCOVA revealed a significant main effect of treatment on students' total test scores [$F(2) = 13.56$, $p < .0001$; Table 6]. The treatment had a significant impact on the students' chemistry achievements. Paired comparisons with a modified Bonferroni correction revealed significant differences between T1 and T2 and between T2 and T3 but no significant difference between T1 and T3. In addition, there was no significant interaction between treatment and teacher [$F(3) = 2.181$, $p = .092$], which indicates that the treatment effect can be generalized to the different teachers in this study without qualification.

We calculated Cohen's effect sizes to determine the magnitude of the treatment effect (summarized in Table 6). The effect size between T1 and T2 was 0.94, representing a large effect (Cohen, 1988), where the mean of the T1 group was around the 82nd percentile of the T2 group (Cohen, 1988). The effect size between T2 and T3 was -0.49 , representing a moderate effect opposite to the predicted direction (Cohen, 1988), where the mean of the T3 group was around the 69th percentile of the T2 group.

In summary, the effect on student achievement was significantly larger for the complete combination of designing, interpreting, and evaluating dynamic molecular models than for only the designing and interpreting modeling activities, and moderately larger for

TABLE 6
Mean (SD) for Total Test Scores

	Treatment			F Value, Paired Comparisons, and Effect Sizes
	T1	T2	T3	
Teacher A	34.83 (12.38)	23.44 (12.37)	22.34 (10.33)	Treatment effect: $F = 13.56^*$ T1/T2, ^a effect size = 0.94 T1/T3, effect size = 0.47 T2/T3, ^a effect size = -0.49
Teacher B	25.58 (11.39)	17.03 (12.92)	25.44 (11.90)	
Teacher C	26.76 (9.27)	11.55 (5.50)		
Total	29.49 (11.65)	18.35 (12.01)	24.09 (11.22)	

Note. T1 = the first treatment (design, interpret, and evaluate); T2 = the second treatment (design and interpret); T3 = the third treatment (view and interpret).

^aSignificant difference at the .05 level.

* $p < .05$.

TABLE 7
Summary of the Statistical Results

Area	Significant Treatment Effect (Effect Size)	Treatment by Teacher Effect	F Value
Total test scores	T1 > T2 (0.94); T3 > T2 (0.49)	ns	$F(2) = 13.56, p < .001$
Content knowledge	T1 > T2 (0.61); T3 > T2 (0.3)	Significant	$F(2) = 7.353, p = .001$
Constructing	T1 > T2 (1.02); T1 > T3 (0.68)	ns	$F(2) = 13.83, p < .001$
Interpreting	T1 > T2 (0.85); T3 > T2 (0.48)	ns	$F(2) = 9.916, p < .001$
Evaluating	T1 > T2 (0.93); T3 > T2 (0.61)	ns	$F(2) = 9.845, p < .001$

Note. T1 = the first treatment (design, interpret, and evaluate); T2 = the second treatment (design and interpret); T3 = the third treatment (view and interpret); ns: not significant.

the viewing and interpreting modeling activities than for the designing and interpreting modeling activities.

The comparison between T1 and T2 supports our prediction that peer evaluations of student-generated animations would have positive impact on students' understanding. The comparison between T2 and T3 indicates that simply viewing improved the learning, since the students who viewed the animation outperformed the other students who only designed their animation. Allowing students to design animations without having them evaluate the animation in terms of the scientific correctness of the model had the lowest effect on their understanding.

In addition to the total test scores, we applied ANCOVA to the students' test scores for content knowledge only and the three aspects of representation skill (constructing, interpreting, and evaluating molecular models). The results indicate the presence of significant treatment effects across all four areas (see Table 7 for the summary). Again, we used paired comparisons with a modified Bonferroni correction to identify the sources of significant differences (Table 7). Overall, the effects were larger for T1, where students designed, interpreted, and evaluated animations, than for T2, where students designed and interpreted animations without peer evaluation. However, T3 students performed significantly better than T2 students in all areas except constructing but the effects were only small to moderate. The hypothesis that the effect on student learning would be better for the designing approach than for the viewing approach was not supported. No significant interaction between treatment and teacher was found for all areas except for students' scores of content knowledge. The treatment effect was uniform across the different teachers.

Students' Visualization of Chemical Phenomena

We compared the quality of student-generated animations between T1 and T2. As indicated in Table 8, the mean scores for the generated animations were significantly higher for

TABLE 8
Mean (SD) Scores for Student-Generated Animations

Treatment	Lesson 5	Lesson 9	Lesson 14	Total
T1	4.7 (1.06)	5.2 (1.03)	5.1 (0.57)	5.0 (0.91)
T2	2.6 (1.71)	2.8 (2.15)	3.6 (1.07)	3.0 (1.70)

Note. T1 = the first treatment (design, interpret, and evaluate); T2 = the second treatment (design and interpret).

TABLE 9
Mean (SD) Scores for Student Interpretation of Animation

Treatment	Lesson 5	Lesson 9	Lesson 14	Total
T1	3.8 (0.92)	4.5 (0.85)	3.4 (0.84)	3.9 (0.96)
T2	3.6 (1.17)	2.5 (2.22)	2.7 (1.25)	2.9 (1.64)
T3	3.0 (1.05)	2.8 (1.14)	3.8 (1.55)	3.2 (1.30)

Note. T1 = the first treatment (design, interpret, and evaluate); T2 = the second treatment (design and interpret); T3 = the third treatment (view and interpret).

T1 students than for T2 students for all three lessons [Lesson 5: $t(18) = 3.298$, $p = .004$; Lesson 9: $t(18) = 3.182$, $p = .005$; Lesson 14: $t(18) = 3.902$, $p = .001$]. The evaluation activity helped students generate higher quality visualizations of chemical phenomena at the molecular level. Most (80%) of the animations created by T1 students showed completely accurate chemistry knowledge compared with only 23% of the animations created by T2 students. In addition to content knowledge, 83% of the animations generated by T1 students incorporated textual representations along with model representations, whereas only 20% of the animations generated by T2 students did so.

Students' Interpretation of Chemical Representation

We examined students' interpretations of the animations during class. One-way analysis of variance indicated that there were significant differences in the students' interpretation scores [$F(2, 87) = 4.242$, $p = .017$]. The mean and standard deviation values are summarized in Table 9. Post hoc comparisons indicated that the significant differences stemmed from the different scores between T1 and T2 and between T1 and T3 but not between T2 and T3. In other words, the interpretations of molecular models were significantly better for T1 students than for T2 students. This result is consistent with the pre- and posttest results.

The absence of a significant difference in the interpretations between T2 and T3 students indicates that T3 students did not experience greater difficulties interpreting the animation and that the student interpretation of dynamic molecular models was no better for the design-only approach than for the viewing approach. It appears that the interpreting ability was as good in students who only viewed chemical representations as in those students who actually created representations.

DISCUSSION AND CONCLUSIONS

The results of this study indicate that the design approach coupled with peer evaluation of student-generated animation is an effective way to use instructional animations. The students who used this approach outperformed the students who designed their animation without peer evaluation. Although it is arguable that such an approach requires more time than the design-only approach, the extra time is well invested. The students who evaluated their animations of molecular processes generated significantly better animations and interpretations and demonstrated a significantly better understanding of chemistry during the posttest phase. This result supports the argument that critique or peer evaluation benefits learning (Linn & Eylon, 2006; White & Frederiksen, 1998, 2000). The animations made by T1 students were more accurate and employed multiple representations that helped the students make connections to the chemical phenomenon and reconstruct accurate chemistry

concepts. The students recognized the importance of using multiple representations in their animations to make them more communicable to others. Although most of the textual representation used was simply a description of the model, its use helped students build connections between the models and the observable phenomena. Studies have found that chemists are fluent in transforming between multiple representations when thinking about the same phenomena and in using representations to facilitate investigations, whereas students rarely show these abilities (Kozma, 2003, n.d.). The findings of the present study suggest that engaging students in peer evaluation can encourage them to use the useful characteristics of a molecular animation, such as including multiple representations to help make connections between molecular representations and macroscopic phenomena.

The results also revealed that the ability to interpret the molecular animation during the learning phase and the understanding of chemistry during the posttest phase were better for students who only viewed the animation than the students who only designed their animation. It suggests that providing students with an inquiry-based curriculum using an age-targeted representation tool (e.g., Chemation for middle school students) would compensate for a viewing-only approach that might not support active learning. The design of Chemation and the inquiry-based curriculum considered the prior knowledge of students, with Chemation reducing the complexity of molecular model representations. This resulted in animations made in Chemation being accessible to seventh-grade students even when they only view the animation.

On the other hand, the results did not favor the design-only approach. Students in the design-only group needed explicit support to help them reflect on what represented a good design, such as constructing content-accurate and multiple-representational animations. It is also possible that the students were cognitively overloaded by the design task since it required certain content knowledge and representation skill, whereas providing time and guidance for evaluation and other reflective activities coupled to the design approach slows the pace so as to facilitate learning.

Future research is needed in several areas that were not explored because of the limitations of this study. First of all, we did not investigate other combinations of the animation-based modeling activities. For example, a comparison between combining the activities of designing, interpreting, and evaluating and combining the activities of viewing, interpreting, and evaluating could indicate whether the effect of the viewing approach is also augmented by the evaluation activity, since we found that the effect of the designing approach was significantly augmented when designing was coupled with peer evaluation. On the other hand, the students in this study demonstrated successful peer evaluation. One conjecture is that the experience of designing animations might simultaneously develop the abilities of the students to evaluate other student-generated animations, because both designing and evaluating experiences involve thinking skills such as deciding between alternative ideas, and this experience after the phase of designing might help the students to evaluate the animations produced by others. This conjecture can be tested by investigating whether students engage in only viewing animations can perform successful evaluations. Future studies should also examine other aspects of the learning environment that were not investigated in this study, such as the role of the teacher in supporting student learning with technology.

APPENDIX A: THE MODELING LEARNING MATERIAL: LESSON 5, T1

Name _____ Class _____

Teacher _____ Your Palm's Number _____

Lesson 5: In this lesson, you will use Chemation to make animations about substances and mixtures at the molecular level.

Planning, Constructing, Interpreting, and Evaluating

Planning: Before you start to build your animation, planning helps you think about what you want to do with the animation, decide how to make your animation and what to include in your animation.

1. What purposes do you have for your animation? In other words, what do you want to show with your animation? Try to describe at least three things.
 - a.
 - b.
 - c.
2. Describe the molecules you start with on the first frame (e.g., What are they? How many do you need for each of them? Do they represent substances or mixtures?)
3. Describe the molecules you end with on the last frame (e.g., What are they? How many do you need for each of them? Do they represent substances or mixtures?)
4. Describe the major changes of atom rearrangement or molecule movement that you are going to make in your animation (e.g., What changes will you make to the molecules on the first frame? Are you going to recombine the atoms or just move the molecules around? Do you add new atoms or molecules in the middle frames?)

Constructing: Chemation is a tool to help you show your ideas through animation.

Now create an animation on Chemation to represent the observation. Type in the title and name like this:


Title:

L5. Your first name (e.g., L5Tina)

Your name:

Your first name and last name (e.g., TinaScott)

5. While you're constructing your animation, check the following things:

a. Did you use "copy frames" () as you make changes?

Yes No

Tip: Using "copy frame" frequently will make your animation look smooth and clear.

b. Did you make a few or too many changes in one frame?

A few Too many

Tip: If you make too many changes in one frame, you will have animation difficult for people to understand. Try to make only one change per frame, or move atoms/molecules a little bit between frames.

c. Did you use the "text tool" (T) to label your model or describe the process?

Yes No

Tip: The text tool in your animation may work as a reminder of the name of the model or the description of the process that you want to demonstrate. However, the use of the feature is optional.

Interpreting: Interpreting requires you to explain what your animation is about and how it relates to your observation. This step is important to show your understanding of both the animation and what it represents.

6. Now recall your observation related to the animation.

a. What does your animation represent? Describe your animation in terms of the experiment.

b. Describe your animation in terms of atoms and molecules. What happened to the molecules and atoms involved?

c. How does your animation make you understand what happened during the experiment? What ideas do you learn from your animation?

Critiquing and evaluating your team members' animation: By critiquing and evaluating your own and classmates' animation, you learn how to improve your animation for a better quality.

7. Beam your animation to your team. You should also collect at least one animation from your team. Evaluate the animation that you collect below.

Animation created by _____

(Name of your team member)

a. Evaluation table

Focus	My Evaluation
Atoms and Molecules	<p>Look at the animation frame by frame. Respond to the following questions.</p> <p>Does the animation include the correct types of molecules to start with? <input type="checkbox"/> Yes <input type="checkbox"/> No. Describe what's incorrect:</p> <p>Does the animation include the correct types of molecules to end with? <input type="checkbox"/> Yes <input type="checkbox"/> No. Describe what's incorrect:</p> <p>Does the animation miss some molecules or atoms? <input type="checkbox"/> Yes. Describe what's missing: <input type="checkbox"/> No</p> <p>Does the animation have extra molecules or atoms that are not needed? <input type="checkbox"/> Yes. Describe what's extra: <input type="checkbox"/> No</p>
Movement	<p>Look at the animation frame by frame. Now focus on the movement, that is, atom connection/reconnection or molecule movement.</p> <p>How do the molecules and atoms move or recombine in a way similar to or different from your animation? The similarities are. . . The differences are. . . I'm confused about this part of the animation. . .</p>
Clearness	<p>Play the animation. Check the following to best describe the animation (you may choose more than one box):</p> <p>The animation clearly shows <input type="checkbox"/> Molecule movement <input type="checkbox"/> Atom movement <input type="checkbox"/> Disconnection between atoms <input type="checkbox"/> Reconnection between atoms</p> <p>The animation did not clearly show <input type="checkbox"/> Molecule movement <input type="checkbox"/> Atom movement <input type="checkbox"/> Disconnection between atoms <input type="checkbox"/> Reconnection between atoms</p> <p>The overall clearness of the animation is <input type="checkbox"/> Very good <input type="checkbox"/> Good <input type="checkbox"/> Not good</p>

b. Overall, what's good about your classmate's animation?

c. What needs improvement?

d. How would you suggest changing the animation to make it better?

e. Discuss the evaluation with your classmate. Take turns to make a summary of your evaluation and suggest ways to help improve the animation. (No need to write down any response here.)

Critiquing and evaluating your own animation:

8. Now you've evaluated your team members' animation and reviewed their evaluation of your animation. Tie all these together, summarize at least three things you've learned from your team member(s).

a.

b.

c.

9. How do you want to change your animation to make it better?

10. Now rename your animation (e.g., L5Tina2) and work on your animation to make it better. (No need to write down any response here.)

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