Chapter 12

The Effect of Student-Constructed Animations versus Storyboards on Students' Mental Rotation Ability, Equilibrium Content Knowledge, and Attitudes

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This study evaluated how general chemistry students' mental rotation abilities, knowledge of physical and chemical equilibrium, and attitudes were affected by the use of one of two different visualization assignments. One class created storyboards with paper and pencil and the other created computer animations with the ChemSense computer program. Both classes showed significant gains in mental rotation abilities and content knowledge, but there was no difference between treatments. No significant differences in content knowledge scores were found between the males and females in the study. However, male students significantly gained in mental rotation abilities over females. In the attitude survey, students believed the activities helped them learn equilibrium content. Both males and females regardless of treatment indicated that the visualization assignments were generally easy as opposed to hard to construct, but females indicated this fact significantly more so than the males. Instructors should be encouraged to use either method to increase mental rotation ability and help with equilibrium understanding.

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ACS Symposium Series; American Chemical Society: Washington, DC, 2013.

Background

Johnstone proposed that chemistry had three basic components: macroscopic, submicroscopic, and representational (*1*). Macroscopic chemistry studies the visible world around us. The submicroscopic component of chemistry describes matter in terms of particles, including their composition and behavior. Representational chemistry is the use of symbols in variables and chemical formulas. This study focuses on the submicroscopic or particulate level of chemistry.

Many high school and college students have trouble understanding scientific concepts and visualizing objects in three-dimensions. A number of researchers have proposed that many student misconceptions in chemistry result from the inability to visualize particles or the faulty visualization of particle behavior (e.g., (*2*, *3*)). Students of chemistry need to be able to correctly visualize atoms and how they are bonded together in three dimensions. José and Williamson (*4*) analyzed the outcomes of a visualization workshop held through the National Science Foundation. They found that the expert participants of the workshop endorsed and proposed the use of visualization techniques in the classroom to promote particle understanding. These participants included chemists, software developers, cognitive scientists, and chemical education researchers.

Previous studies have analyzed different methods of helping students learn how to visualize chemical and physical processes. Sanger (*5*) investigated the understandings of college students in a general chemistry course. He found that: "students who received instruction that focused on the characteristics of pure substances and mixtures at the microscopic level were more likely than students who received traditional instruction at the macroscopic level to correctly identify particulate drawings of liquids, pure compounds, heterogeneous mixtures, homogeneous mixtures, elements, and compounds. (pp765-766)" He concluded that instruction using particulate drawings and computer animations are very useful in helping students correctly answer questions about chemical processes.

Visualization can be a powerful tool to help explain chemical processes and properties. Williamson and Abraham (*6*) found that short duration animations used during lecture in a 2-week unit of study on gases, liquids, and solids significantly improved general chemistry students' conceptual understanding. These authors repeated the study with a unit on reaction chemistry. The finding of significant improvements in conceptual understanding for the treatment group that received instruction using particulate animations was the same. Sanger and Badger (*7*) studied how to best communicate the concepts of molecular polarity and miscibility. They found that college students exposed to computer animations and electron density plots gained a better understanding of molecular polarity and intermolecular forces.

Student-generated drawings/animations can be used to evaluate student understanding, although they may be hard to interpret/grade (*5*). One way to ascertain student understanding is to ask students to draw their ideas. Harrison & Treagust (*8*) used student drawings to evaluate student understanding. They proposed that students should receive instruction with visualization techniques appropriate to their cognitive ability; however, instructors should gradually challenge students to use more abstract models. Further, multiple models should be used in instruction. A case study was used to explain how the systematic use of models improved a high school chemistry students' understanding of atoms and molecules.

Milne (*9*) reported the effects of using index cards to model chemical reactions. Students at the secondary level were given 20 index cards to model a chemical reaction by creating a "flip book." This allowed students to visualize the motion in a chemical reaction, as well as the kinetic and stoichiometric properties of reactions. He found that students became very engaged while they created storyboards (in the form of note cards) to simulate chemical reactions. Storyboards were proposed as an effective way to actively engage the students and to teach chemical reactions, even though the study did not investigate the impact on content knowledge.

There is some evidence that student creation, rather than just presentation, of models can lead to enhanced understanding. With computer programs, students can produce their own animations. Schank and Kozma (*10*) investigated ChemSense, a molecular drawing and animation tool. In one of the reported experiments, high school students who used ChemSense had a significant improvement in their understanding of connectivity and geometry of molecules from pre- to post-test. Also, a positive correlation was found between the number of drawings and animations produced in a 3-week unit and the chemical correctness of the animations produced. From the video recordings of students working on their animations, the authors propose that students were able to better represent chemical phenomena at the particulate level as a result of the planning and consideration of what to put in each frame of the animation. Students were more focused on aspects of the chemical phenomena that they would not normally consider, including the geometry, the sequence of steps, and the dynamic nature of chemical reactions

While storyboards and animations may help student understanding, previous research has also found a link between having good spatial abilities and performing well in chemistry courses. Spatial abilities include a number of visuo-spatial abilities, of which mental rotation ability, the ability to rotate in three dimensions, is a major component (*11*). In organic chemistry courses, students with high spatial abilities as measured by a mental rotation test and a hidden shape test did significantly better on questions which required problem solving skills, but no different on rote-memory questions (*12*). Further, high spatial students drew molecules in three dimensions without being prompted when answering questions and were more likely to get problems correct (*12*). In a similar study, students who score higher on the same spatial ability tests are more likely to perform well in general chemistry courses (*13*). This suggests a link between spatial abilities and performance in chemistry, at least during the first two years of college chemistry. Finally, it has been shown that there is a significant lack of spatial abilities amongst college students regardless of gender (*14*), and that there is a need to address this problem.

This study investigated two different means to foster student understanding of particles (student-constructed storyboards and animation) and to compare the effectiveness of the two treatments when using the concepts of physical and chemical equilibrium. It also focuses on mental rotation abilities and performance on a chemistry content quiz dealing with these concepts. A number of researchers have found that students lack a conceptual understanding of equilibrium (e.g. (*15*)). In this study, college students were assigned projects (either to construct storyboards or animations) to determine their understanding of the concepts of chemical and physical equilibrium. When students are assigned a project, they must be creative, ask questions, and take responsibility for their own learning. Students were required to construct a mental model of a process in their minds and express it. Constructivism is the theoretical frameworks behind this style of teaching/learning.

In constructivism, the student-learners are guided by a facilitator, but students take the bulk of the responsibility for their own learning (*16*). Bodner (*17*) states that "[k]nowledge is constructed in the mind of the learner." He also makes the case that a teacher should facilitate learning, and not simply attempt to transfer knowledge into the minds of the students. The Constructivist model of learning is greatly influenced by the work of Jean Piaget. Piaget believed that we can learn about another's mental mindset by observing this individual's behavior. He also stated that a person's intellectual growth is linked to his physical and social environment. Finally, he used the fact that humans are a biological species as an influence to theorize that we are motivated to grow and change by a process of "organization and adaptation" (*18*). Piaget has had a profound impact on educational research (*19–21*). The philosophy of Lev Semenovich Vygotsky also has had an influence on constructivism. Vygotsky believed in cooperative learning and that a student will learn with instructional help. Every learner has a Zone of Proximal Development (ZPD), which is the gap between what the learner knows and what they are capable of learning with help. With time, the learner will be able to perform certain tasks without assistance (*22*).

The purpose of this study was to investigate the effectiveness of two visualization techniques, student-constructed storyboards and animations. The goal was to analyze how these techniques can help students better understand equilibrium concepts and better visualize objects in three dimensions.

Research Questions

The specific research questions are:

1. How are general chemistry students' mental rotation ability and equilibrium content knowledge affected by the construction of computer animations or the construction of storyboards?
2. What are students' attitudes toward drawing three-dimensional molecules with computer animations or with paper and pencil?

Research Procedures

This research project involved two college classes of second semester general chemistry at a large southwestern university. Each class contained approximately

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300 students. The first activity given to the students was a pre-test, which occurred before any instruction on equilibrium was given in the lecture or the laboratory portions of the courses. This test contains seven multiple-choice questions, each one related to equilibrium, and was given in class as a quiz for a quiz grade. These questions were conceptual based, and the math required was minimal. Scores on the content pre-test ranged from 0-7. A few sample questions are included in Table 1.

Table 1. Sample Pre-test Questions

3. For the reaction A(g) + B(g) $\leftrightarrows$ C(g) + D(g), K = 0.001. Which statement best describes this reaction at equilibrium? a) There is much more A and B than C and D. b) There is much more C and D than A and B. c) There are equal amounts of A, B, C, and D. d) The reaction has gone to completion; all of the A and B have been depleted.
5. Which of the following is ALWAYS TRUE about chemical equilibrium? a) At equilibrium, the chemical reaction stops. b) If K = 10, then the forward reaction rate is faster than the reverse reaction rate. c) The equilibrium constant is independent of reactant concentration. d) At equilibrium, the concentrations of all reactants and products are the same.
7. The following reaction, 2A(g) $\leftrightarrows$ B(g), has concentration of A and B as 2 M and 1 M, respectively. If the equilibrium constant is 0.50, what can be said about this reaction? a) The reaction is at equilibrium. b) The reaction is not at equilibrium, and more products will be formed until equilibrium is established. c) The reaction is not at equilibrium, and more reactants will be formed until equilibrium is established. d) The reaction is not at equilibrium, and the reaction will shift until the concentrations of the reactants and products are the same.

The students were then assigned to take an online assessment, which tested their mental rotation ability. The Vandenberg Mental Rotations Test, Vandenberg Test, or MRT is widely used and requires students to answer questions related to the rotations of three-dimensional shapes. Vandenberg and Kuse (*23*) reported that this test has internal consistency and reliability between taking the test multiple times, and differences in results between males and females. Each question provides a three-dimensional object in picture form and asks for the student to indicate which two of the four choices illustrate the same object, which has been rotated in some manner. There are 20 total questions (each worth two points), and the test is split into two sections of 10 questions each. Each student was given three minutes to complete the first half and another three minutes to complete the second half. The computer programming did not allow the student to return to a previous page and moved forward once three minutes of time had passed. There are two correct

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answers to each question. If a student selects only the two correct choices for a question, two points are awarded. If a student selects one correct choice and one incorrect choice, zero points are awarded. If only one correct choice is selected and no others, one point is awarded. Finally, if a student does not answer a question, no points are awarded.

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Immediately after the Vandenberg Test was completed, each lecture class of students was asked to create a model of a physical equilibrium via different means. A coin flip was used to determine the treatment (storyboards or ChemSense animations) assigned to a lecture class. Students in each lecture class were divided into groups of 24 for laboratory. Students were assigned a physical system to model from a list of 24 possibilities. They were later assigned a chemical reaction to model from a list of 24 possibilities. For example: One student could be assigned to model the equilibrium established between liquid and gas phases of H_2O ($H_2O(l) \leftrightarrows H_2O(g)$) and the equilibrium involved with the chemical reaction $H_2(g) + I_2(g) \leftrightarrows 2HI(g)$. With the pool of 24 physical and 24 chemical equilibria, every student in a laboratory section was assigned a different physical and chemical process. The assignments were randomized such that the physical equilibrium was not paired with the same chemical equilibrium, so students in the second laboratory would not have the same pairings as students in the first laboratory. One assignment may be more difficult than another, but each laboratory section was assigned the same set of problems and the averages of the scores on these assignments were analyzed. The assignments for the two treatments (storyboards or ChemSense animations) were from the same list of choices and done in the same manner. All of the students were given a week to perform the activity for physical equilibrium and a second week to complete a chemical equilibrium.

One lecture class (broken into 12-13 laboratory sections) was assigned to create two animations that simulated the two different assigned equilibria using the ChemSense computer program (*10*). ChemSense had been used previously at this institution. Students in first and second semester general chemistry had been asked to use it to model chemical reactions that go to completion during six previous semesters. It should also be noted that ChemSense is easy to use and has been used as a tool in education research as previously discussed (*10*, *24*). A short, two-page tutorial guide that had been provided to students in these past semesters was also used in this study. The tutorial walks students through the construction of a trial animation of hydrogen gas plus oxygen gas forming water. Students were told that their animation should contain at least 10 frames and were given the grading rubric (see Table 2).

Table 2. Scoring Rubric for Both Storyboards and ChemSense animations

8 pts	At least 10 frames long, 1 pt Chemically correct, 2 pts • Atoms are correctly bonded together, 1 pt • Atoms are labeled correctly, 1 pt Equilibrium illustrated correctly, 5 pts • The forward and the reverse processes must be illustrated, 2 pts • Once equilibrium has been established, there must be reactant molecules changing into products at the same rate that product molecules are changing into reactants, 3 pts

The other lecture class was required to create storyboards to model the assigned physical and chemical equilibria. Students were told that a storyboard is a series of still pictures to mimic motion. Further they were told that their storyboard should contain at least 10 pictures and were given the grading rubric. Table 2 provides the rubric (which was made available to all students) for grading the storyboards and ChemSense assignments. A student must have the correct proportion of atoms drawn for the molecule in order to receive full credit for the chemically correct portion of the rubric. Also, the forward and reverse processes in equilibrium must be illustrated clearly.

Once the students had all completed their assignments of modeling a physical and a chemical equilibrium, the students were given the post-test (as a quiz grade) in the lecture class. The post-test is similar to the pre-test, but contained different questions related to equilibrium. There were seven multiple-choice questions on the post-test, conceptually based, and therefore the scores ranged from 0-7. The post-test also asked students questions about their attitudes toward drawing molecules with the use of ChemSense or with pencil and paper, using one semantic differential question and five open response questions. Finally, students were given the Vandenberg Test again, which was again offered online. The second iteration of the mental rotations test was given about five weeks after the first iteration, to help negate gains from just retesting. The order was such that content pre-test, the first Vandenberg Test, the equilibrium unit of study, and the post-test were followed by the second mental rotation test.

The instructor routinely gave the Test of Logical Thinking (TOLT) to her classes as a quiz near the beginning of the course to help gauge the level of mathematics instruction needed. The TOLT tests one's ability to understand control of variables, proportionality, combinations, correlation logic, and probability logic. The TOLT has a high reliability (*21*, *25*) as students must get both the correct answer and reason for their answer in order to receive credit for an item. There are ten total questions on the TOLT; therefore a student can earn a score of 0-10.

Quiz credit was offered for the TOLT, pre-test, post-test, and both administrations of the Vandenberg test (which will from this point be referred to as MR ability I and MR ability II). The two classes required 11 quizzes (at 4 points each), but typically 19-20 were given throughout the semester. Quiz credit constituted 44 points out of a total 1000 points for the course. The classes also required 16 points of special assignments, which can include projects, seminar summaries, take-home worksheets, etc. Eight points of special assignment credit were offered for each of the two visualizations produced (ChemSense or storyboards). Students were asked to participate in the study by releasing their grades for the TOLT, pre-test, post-test, MR ability I and MR ability II. The storyboard class had 143 students participate in the research project; while the ChemSense animation class had 157 students participate.

After the students took the Pre-test, TOLT, and MR ability I, they were exposed to the specific equilibrium material in lecture, laboratory, and in the assignments of ChemSense and storyboards. They obviously learned from all of these sources. The purpose of this study is to analyze the value added, if any, when students use electronic (ChemSense) or paper and pencil (storyboards) means to study chemistry material. The data from the TOLT was analyzed to determine group equivalency. An analysis of the pre-test vs. the post-test scores was done to determine if learning has occurred for each group. Also, an analysis between the gains for each group investigated any differences on content learning between the two treatment groups. Similar analysis of the mental rotation ability data determined if there have been any changes pre- to post- within each group and if there are any changes, if these differ between the two treatment groups. Also, the students' attitudes between the two treatment groups were compared and contrasted. As a series of two-tailed t-tests are required for all these analyses, a MANOVA was also used to help control error.

Results

Table 3 reports the average scores of both groups on the TOLT, pre-test, and post-test, in addition to their average age. Age was calculated by asking the students to enter their birthdays online when they took the Vandenberg Test. The TOLT is scored out of ten points, and the pre- and post-tests are both scored out of 7 points. The students took the Vandenberg Test twice, MR ability I first and then MR ability II, which are reported in Table 3. The second time the students took this test, they had completed all of the storyboard or ChemSense assignments. The Vandenberg Test is scored out of 40 points.

Table 3. Means and Standard Deviations for Age, Reasoning Ability, Content Tests, and Mental Rotation Abilities

	Storyboard (n = 143)	***Animation (n = 157)***
	Mean (SD)	*Mean (SD)*
Age	19.19 (1.67)	18.90 (0.60)
TOLT	7.84 (1.89)	7.47 (2.01)
Content Pre-test	2.52 (1.22)	2.40 (1.27)
Content Post-test	4.41 (1.43)	4.42 (1.48)
Mental Rotation Ability I	15.85 (6.48)	15.81 (8.12)
Mental Rotation Ability II	20.32 (8.68)	20.05 (9.64)
Physical Equilibrium Grade	5.60 (2.02)	6.13 (1.79)
Chemical Equilibrium Grade	5.12 (2.08)	6.06 (2.14)

Each equilibrium assignment was graded out of eight points. The majority of the points were given for depicting a conceptual understanding of equilibrium. Table 3 also summarizes each group's average scores on the physical and chemical equilibrium. Each assignment was scored by the second author. These scores were randomly checked by another rater who used the same rubric, with a 94% inter-rater agreement.

There was a total of six questions on the attitudinal survey given with the post-test. The mean was calculated for the first survey question. This 7-point, semantic differential question asked students to rate the visualization assignments' difficulty level. Table 4 shows these data.

Table 4. Scores on the Semantic Differential Question Given on the Survey

Question	***Storyboard (n = 143)***	***Animation (n = 157)***
	Mean (SD)	*Mean (SD)*
1. How easy was it for you to produce the assigned visualizations? Please circle only one number. Easiest 1 2 3 4 5 6 7 Hardest	3.34 (1.32)	3.17 (1.20)

Questions 2, 3, and 4 asked the students to answer yes or no and to explain. Some students did not choose yes or no, so were coded as undecided. The tallies of the yes (Y), no (N), and undecided (U) responses are reported in Table 5. The Animation Group had a higher fraction of students respond favorably (indicating yes) to all three of these questions than the Storyboard Group.

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Table 5. Questions Requiring Both an Answer and an Explanation on the Survey

	Storyboard (n = 143)			***Animation (n = 157)***		
Question:	*Y*	*N*	*U*	*Y*	*N*	*U*
2. Did producing the required visualization help you learn chemistry content (yes or no)? Please explain.	95	46	2	111	46	0
3. Did producing the required visualization help you to better visualize objects in three-dimensions (yes or no)? Please explain.	75	68	0	102	55	0
4. Were the benefits of producing the required visualization worth the time it took to produce them (yes or no)? Please explain.	79	58	6	94	60	3

There were five opportunities for open responses on the survey. Questions 2-4 in addition to asking for the yes or no responses, which were reported in Table 5, also gave each student the opportunity to explain the response. Questions 5 and 6 allowed students express his/her point of view about the visualization assignments when asked what was the best part and what was the worst part of producing the required visualization. Examples of some responses to all these questions are provided in Table 6. These examples are representative of both the positive and negative comments given.

Analysis

Both the Animation and Storyboard Group averaged above 7 on the TOLT. In the 1981 initial validation study, college students enrolled in science courses scored an average of 4.4 on the TOLT (*21*). In another study, two groups of college students enrolled in a junior-level quantitative analysis course scored above 8 on this test (*25*). It is clear that both groups in this study understand important mathematical concepts and can think logically.

A MANOVA was performed to determine if the two classes were statistically equivalent based on a variety of dependent variables. Table 7 reports the results for their TOLT scores. There is no statistical difference between the two groups with respect to their TOLT scores.

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Table 6. Responses to the Open Questions Given on the Survey

2. Did producing the required visualization help you learn chemistry content (yes or no)? Please explain.	
Storyboard Group	***Animation Group***
• Yes, [it] reinforced understanding of how molecules behave in trying to achieve equilibrium. • No it did not. I already understood equilibrium. • Yes, I could see how the reaction progressed in both directions.	• No, I already understood the concepts. • Yes, had to think for ourselves how reaction occurred. • No, I already knew what equilibrium meant, doing the animation was a pain. • Yes, it helped me understand equilibrium and its relationship with reactants and products.
3. Did producing the required visualization help you to better visualize objects in three-dimensions (yes or no)? Please explain.	
Storyboard Group	***Animation Group***
• Yes, because I am a visual learner. • No, the drawings were two-dimensional.	• Yes, it did help me visualize it better. • No, I have never been good at visualizing 3D objects.
4. Were the benefits of producing the required visualization worth the time it took to produce them (yes or no)? Please explain.	
Storyboard Group	***Animation Group***
• Not at all. I could have visualized it in my head. • It didn't take too long and it helped me to see the reaction.	• Yes, because they did not take very long. • No, it took a long time for me.
5. What was the best part of producing the required visualization?	
Storyboard Group	***Animation Group***
• It was better than having to write a paper to try to explain it. • Quick and easy, not just homework but something different.	• Making a chemistry movie was kind of fun. • Watching the animation once it was done.
6. What was the worst part of producing the required visualization?	
Storyboard Group	***Animation Group***
• It was time consuming and I'm bad at art. • Filling in 10 slides, didn't need 10.	• The time it took to make. • Program slightly confusing and it took a while to get the molecules to do what you wanted them to do.

Table 7. MANOVA Results between the Storyboard and Animation Groups

	p-value
Age	0.0451[a]
TOLT	0.0978
Content Pre-test	0.3914
Content Post-test	0.9299
Mental Rotation Ability I	0.9652
Mental Rotation Ability II	0.7945
Physical Equilibrium Grade	0.0162[a]
Chemical Equilibrium Grade	0.0001[a]

[a] significant difference, $p < 0.05$

The Storyboard Group was statistically significantly older ($p = 0.0451$) than the Animation Group. However, no changes in the results were found when age was used as a covariant. For the TOLT, content and MR ability measures taken by the two groups, there was no significant difference between groups. There was, however, a significant difference in the grades received on the equilibrium projects ($p = 0.0162$, $p = 0.0001$). The Animation Group scored significantly higher in modeling the physical and chemical equilibrium processes than the Storyboard Group. It is not clear why there should be a difference in scores on the equilibrium assignments. When looking at the grading rubric in Table 2, there does not appear to be a bias.

Table 8 reports the comparisons between changes within the groups on content and mental rotation ability. Content knowledge is gauged with the administrations of the pre-test and post-test (see Table 3). There is a significant gain in understanding in course content; hence there was a rise in scores for both groups between the pre- and post-tests. Additionally, MR ability II is statistically significantly higher than MR ability I, regardless of the treatment group. Both groups increased in content knowledge of equilibrium and increased in mental rotation ability during the equilibrium unit of study, which lasted about 4 weeks and was between the pre- and post- content tests.

Table 9 reports each treatment group by gender. Within the Storyboard Group, there was a significant difference in comparing MR ability II and survey question #1. Males scored significantly higher on MR ability II. Females believed that the task of producing the assigned visualization was easier than the males believed. Within the Animation Group, a significant difference was observed when comparing the results for MR ability I and MR ability II. Males scored significantly higher than females on both of these tests. Also, there was a significant difference in the responses to survey question #1. Females in each treatment group indicated that producing the visualization assignment was an easier task more so than the males in the group.

Table 8. MANOVA Results for Changes in Content and Mental Rotation Ability

	p-value
Content Pre-test to Content Post-test	
Storyboard Group	<0.0001[a]
Animation Group	<0.0001[a]
Total	<0.0001[a]
MR Ability I to MR Ability II	
Storyboard Group	<0.0001[a]
Animation Group	<0.0001[a]
Total	<0.0001[a]

[a] significant difference, $p < 0.05$

Table 9. MANOVA Results by Gender within each Group

	Storyboard Group *p-value*	***Animation Group*** *p-value*	***Total*** *p-value*
Age	0.3958	0.8279	0.4125
TOLT	0.5223	0.1093	0.0603
Content Pre-test	0.5934	0.5439	0.6762
Content Post-test	0.2118	0.1489	0.0635
Mental Rotation Ability I	0.2491	0.0005[a]	0.0002[a]
Mental Rotation Ability II	0.0119[a]	0.0002[a]	<0.0001[a]
Physical Equilibrium Grade	0.1767	0.5886	0.1039
Chemical Equilibrium Grade	0.4576	0.4328	0.6272
Survey Question #1	0.0247[a]	0.0225[a]	0.0016[a]

[a] significant difference, $p < 0.05$

For the total study population, composed of both treatment groups, there were significant differences for MR ability I, MR ability II, and survey question #1. Males scored significantly higher than females in both iterations of the MR Abilities Test. For survey question #1, the means were 3.42 (SD=1.28) and 2.94 (SD=1.17) for the males and females, respectively. Once again, females indicated that the task of producing the assigned visualizations was an easier task than the males indicated. Although the females thought the visualizations were easier to produce, the mean for the males was still below the neutral midpoint of 4.

The content gain was found by subtracting the pre-test from the post-test. The mental rotation ability gain was found by subtracting MR ability I from MR ability II. These gains were investigated to see if there was a difference in the gain by gender, and the results are reported in Table 10.

Table 10. MANOVA Results in Comparing Changes in Content and Mental Rotation Ability by Gender

Content Gain (Content Post-test minus Pre-test)	***Males Mean (SD)***	***Females Mean (SD)***	***p-value***
Storyboard Group Males to Females	2.16 (1.65)	1.73 (1.77)	0.1608
Animation Group Males to Females	2.19 (1.63)	1.94 (1.62)	0.3872
Total Males to Females	2.12 (1.66)	1.86 (1.71)	0.1995
Mental Rotation Ability Gain (MR Ability II minus MR Ability I)	***Males Mean (SD)***	***Females Mean (SD)***	***p-value***
Storyboard Group Males to Females	6.12 (8.01)	3.62 (5.35)	0.0506
Animation Group Males to Females	5.11 (7.11)	3.90 (7.24)	0.3317
Total Males to Females	5.65 (6.19)	3.62 (7.58)	0.0184[a]

[a] significant difference, $p < 0.05$

The mean of the difference between the post-test and the pre-test is a positive number for both males and females. Also, for males and females, the mean of the difference between MR ability II and MR ability I is a positive number. However, no significant difference was found in these gains when comparing males and females, except when the total number of males and females were compared in regards to their respective gains in mental rotation abilities. Males gained significantly more in mental rotation abilities than females in this study. The averages for the pre-test, post-test, MR ability I, and MR ability II for the total males and females are provided in Table 11.

Paired t-tests were performed comparing the results, by gender, of the content pre-test to the post-test, as well as comparing MR ability I to MR ability II. Within the Storyboard and Animation Groups, males scored significantly higher on the post-test than the pre-test (p-values < 0.0001). Also, males, within each group, scored significantly higher on MR ability II than MR ability I (p-values < 0.0001). Finally, the total male population significantly raised their scores from the pre-test to the post-test and from MR ability I to MR ability II (p-values < 0.0001).

Table 11. Averages of Content Tests and Mental Rotation Ability Tests for Males and Females

	Males mean (SD) (n = 108)	*Females mean (SD) (n = 192)*
Content Pre-test	2.50 (1.15)	2.44 (1.29)
Content Post-test	4.62 (1.44)	4.30 (1.45)
MR Ability I	17.95 (7.57)	14.63 (7.00)
MR Ability II	23.60 (9.16)	18.25 (8.64)

The exact same results for the females resulted from the paired t-tests. Females significantly raised their scores from the pre-test to the post-test and from MR Ability I to MR Ability II within each group and when the total female population was considered (p-values < 0.0001). It is clear that both males and females of this study gained in equilibrium content knowledge and in mental rotation abilities.

The three survey questions that required yes-no answers listed in Table 5 were analyzed using a chi-squared test. The undecided responses were combined with those that responded negatively. Using the idea that we expect no differences between the Storyboard and Animation Groups, we used a theoretical probability of an even distribution. Using these expected values, all three questions were significantly different ($p < 0.05$) between the two groups.

Discussion

The first research question was: How are general chemistry students' mental rotation ability and equilibrium content knowledge affected by the use of computer animations or the use of storyboards? The students gained in their mental rotation ability during the length of the research project. Both groups significantly improved their mental rotation ability scores; however, there was no difference between treatment groups. There was a gender effect for the total study population. It is interesting to note that males scored higher than females on both iterations of the Vandenberg Test. This result fits with the findings in the literature that males typically have a better ability to spatially-visualize objects in three dimensions. Barke (*26*), for instance, reported that males score higher on spatial ability tests than females of the same age. His study focused on students in 7th through 9th grades. For the total sample of this study, the gains in mental rotation abilities for males were significantly higher than the gains for females. Vandenberg and Kuse reported similar findings in their work with college students (*23*). Females, in both treatment groups and as a whole, significantly gained in mental rotational abilities from their pre-test to their post-test, which is consistent with previous research (*27*).

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It is clear that students in both groups gained in content knowledge after being assigned to model two different processes, one physical and one chemical. During this time, they were also exposed to course material from the lecture and lab portions of the course, so the increase in understanding cannot be attributed to the visualization assignments alone. However, both groups had similar content gains. It does not seem to matter which method is used (computer animation or storyboard). It is interesting to note that in survey question #2, the majority of both treatment groups believed the visualization assignments helped them learn chemistry content.

It is unclear as to why the Animation Group scored significantly higher than the Storyboard Group on both equilibrium projects. On examining the rubric for grading the visualization project, no bias in favor of the Animation Group could be found. It could be that college students are more comfortable with a computer interface than using traditional pencil and paper. No evidence was found in this study suggesting that college students have a better ability to use a computer interface than pencil and paper. The ChemSense software is easy to use, and very little effort is needed to model a molecule moving, shifting, and having its bonds break and reform. ChemSense has features (such as labeling an atom automatically) that could provide students an advantage over the ones who were assigned to create a storyboard. In the rubric, one point was given for labeling the atoms correctly, so this might explain the difference.

The visualization assignments resulted in uncovering a number of student misconceptions, regardless of treatment. These misconceptions are similar to those reported by others (*15*). Some students would depict the reactants all going to products, then remaining static. While others would show the reactants going to all products, then the products going back to all reactants. It could be that they were misunderstanding the term 'reversible.' Some students would show half of the reactants going to products, then remaining static with an equal mix of products and reactants.

There was one observation that may explain the similarity of the two treatment groups. Many students in the Storyboard Group made flipbooks from their static pictures without any instructions indicating this was a possibility. The Storyboard Group was told: "A storyboard is a series of still pictures that mimics motion. Please draw each one of these pictures on a 3 inch by 5 inch note card. Also, please have your story board be no shorter than ten pictures." We believe that the process for making the pictures for the storyboard was not very different from the process needed to construct a frame for the ChemSense animation. Figure 1 depicts a sample storyboard.

The second research question was: What are students' attitudes toward drawing three-dimensional molecules with computer animations or with paper and pencil? For both treatment groups (Storyboard and Animation), students believed that the assignment was relatively easy. For both groups, the means of survey question #1 were less than the midpoint of 4, which indicates that they believed, as a whole, that the assignments were easy, rather than hard to complete. Also, both males and females indicated the ease of producing the assignment with an average below 4. There was only one gender effect in the attitude survey. According to their responses to survey question #1, females

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believed that producing the equilibrium assignments was an even easier task than did the males of this study.

There were some interesting comments made on the other survey questions. Some students believed that the assignment was a worthwhile exercise, and some believed that it was not. It is interesting that some students commented that they enjoyed the assignment because it was different than what they are used to in a college science course. It seems to be a rewarding experience for them to participate in an alternate assignment from the normal routine of doing online homework and taking tests. Finally, some students completed the assignment in a short period of time, according to their comments, and others believed that it was a time-consuming task. The Animation Group seemed to answer more favorably to the attitude questions that asked for yes or no responses (Table 5). It is unclear as to why the Animation Group would believe to a greater extent that this project helped them to learn chemistry content and to visualize objects in three-dimensions, plus was worth the time. More of the students in the Animation Group believed the animations helped them learn content and that the MANOVA tests showed that the students in the Animation Group did learn more chemistry content (i.e., their perceptions were matched by the analysis of their post-test responses).

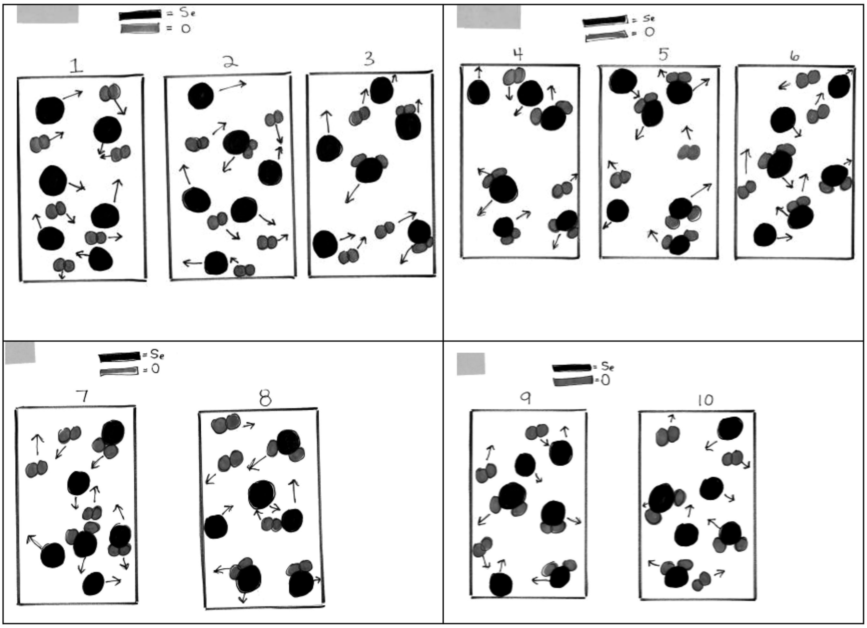

Figure 1. Sample Student Storyboard for Se(g) + O_2(g) $\rightleftharpoons$ SeO_2(g)

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Summary

This research project documented how students' mental rotation abilities and content knowledge changed when exposed to one of two methods of modeling an equilibrium process: an animation computer program and a storyboard with paper and pencil. The students significantly gained in equilibrium content knowledge and significantly gained in mental rotation ability, regardless of the method used (storyboards or ChemSense animations). By having students represent the concepts themselves, students are taking an active role in their learning.

This study found that males had a significantly better ability to rotate three-dimensional objects as measured by the Vandenberg test than did the females. Both males and females gained significantly in their mental rotation abilities throughout the course of this project. However, the males' mental rotation ability over the project increased significantly more than that of the females.

Classroom Implications and Further Research

Instructors of general chemistry in college, as well as high school chemistry teachers, should consider including activities designed to help improve the spatial abilities of their students for the following reasons: (a) having good spatial abilities can better equip students to be successful in chemistry (*12*, *13*) and (b) it has been shown that mental rotation ability can be increased in this study and reported by a number of others (e.g. (*28*)). Spatial ability tests, especially mental rotation tests, could be included early in a course to gauge student ability to visualize. In general chemistry and beyond, students need to be able to visualize molecules in three-dimensions, draw them correctly, and answer questions that pertain to their behavior. Exposure to particulate or three-dimensional molecules may be needed throughout courses (*4*). Instructors can use either storyboard or animation assignments to help with equilibrium understanding and mental rotation ability. Each instructor can make the decision about which method would work best after reviewing the logistical situation and resources available at their own institution.

Further research needs to investigate whether storyboards or animations have any effect with other concepts in chemistry. It should be noted that students still have difficulty with equilibrium; therefore, research on how to improve students understanding of physical and chemical equilibria is also needed.

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