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"Concept Learning versus Problem Solving": Does Particle Motion Have an Effect?

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In 1987, Nurrenbern and Pickering *(1)* published an article titled "Concept Learning versus Problem Solving: Is There a Difference?" in which they showed that students who can solve mathematical chemistry problems often have difficulty in answering conceptual problems covering the same topics, especially if these problems address concepts at the particulate level. Twenty years later, several chemical education researchers have corroborated these results *(2–7)* using the particulate pictures reported by Nurrenbern and Pickering and other pictures *(8–18)*.

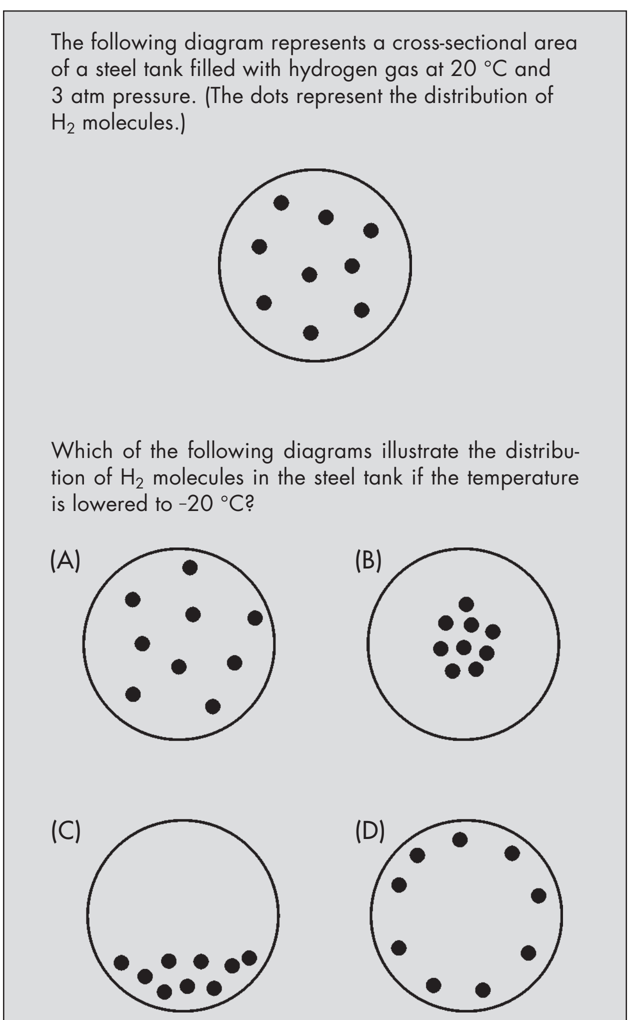

Figure 1. Adapted[1] from a multiple-choice question reported in Nurrenbern and Pickering *(1)*.

This study focused on one of the particulate pictures used by Nurrenbern and Pickering, which appears in Figure 1. The question was altered slightly from its original form so that the number of particles in the "before" and the four "after" pictures were the same. While several researchers have used this question *(1–5, 7, 9, 10)*, only recently has an analysis of students' molecular-level explanations of this question been reported *(7)*. In that study, Sanger and Phelps identified three threats to the validity of this question (and its ability to measure students' conceptual understanding of gas particle behaviors). One of these threats is that the critical attribute that changed when the gas sample was cooled (particle motion) cannot be shown by the static multiple-choice question. This is a problem because some students were reluctant to pick the correct answer (A) because that picture looked no different from the starting picture, but they were sure that decreasing the temperature would have some effect on the particles. The other two threats to validity were that some students view options (B) and (C) as equivalent answers depending on how the cross-section of the tank was cut, and that students who said the gas sample would liquefy or solidify may not be demonstrating a misconception—they simply misidentified the conditions under which these changes would occur.

An animated version of this question would certainly allow students to see how particle motions change as a result of cooling the gas sample, and could address the other two threats as well. This study investigated two research questions:

1. Will students' responses to this question improve after viewing the animation?
2. Which (if any) of the three threats to validity does the animation address?

Several chemical education research studies have shown that computer animations of chemical processes at the molecular level are effective at improving students' conceptual understanding when used as part of instruction *(11, 15, 19–24)*, and a summary of the theories explaining why animations should improve learning (including Paivio's Dual Coding Theory and Mayer's Cognitive Theory of Multimedia Learning) has been previously described *(25)*. In his review on the effectiveness of computer animations, Rieber *(26)* noted that animations are most effective when the instructional topic involves the attributes of visualization, motion, or trajectory. Since this question requires students to consider molecular visualization *(27)* and particle motion, it is not unreasonable to believe that viewing the animated question would affect students' responses. Most of the prior research studies on the use of computer animations to improve students' conceptual understanding of chemistry have used the animations as part of the instructional lesson. This study, on the other hand, is one of the first to measure the effect of a computer animation as part of the assessment of conceptual understanding.

Methodology

Subjects

This study included students enrolled in the 12 sections of second-semester general chemistry taught during a single semester ($N = 210$). The data were collected during a three-hour lab period while the students were performing an unrelated laboratory experiment.

Research Design

This study utilized a one-group pretest–posttest design *(28).* Each student was asked to answer the static question (pretest). Then each student viewed the animation (experimental treatment) for 5–10 minutes and when they felt they had seen enough they were allowed to answer the question again (posttest). The students were also asked whether any of the particles in the animation were moving differently from what they had expected and were asked to explain why they chose the option that they did. The total time needed for each student to finish this experiment was less than one hour.

Data Analysis

The distributions of student responses to the static and animated question appear in Table 1. Although we are comparing frequency data, we cannot use a simple χ^2 test of homogeneity because it requires the two groups to be independent of each other, which clearly is not true since they are the same population. Therefore, we used a McNemar test for significance of change *(29).* This statistical test compares student responses that have changed as a result of an instructional treatment (i.e., students' responses that did not change are ignored) to a random distribution of changes. Table 2 contains data showing the distribution of student responses to the static and animated question. For each entry in Table 2, the column represents the students' choice before viewing the animation and the row represents their choice after the animation. For example, there were 42 students (first entry in the second column) who chose (B) before viewing the animation but changed their answer to (A) after the animation. The "static" data in Table 1 come from adding up each of the four columns in Table 2; the "animated" data come from adding up each of the four rows in Table 2. Because the expected

Table 1. Distribution of Student Responses to a Multiple-Choice, Particulate Representation Question

Data Source (Number of Responses)	Student Response Choices (A Is the Only Correct Response) A	(%)	B	(%)	C	(%)	D	(%)
Nurrenbern and Pickering *(1)*, (N = 198)[a]	72	(36)	56	(28)	50	(25)	11	(6)
Sawrey *(2)*, (N = 285)[a]	89	(31)	136	(48)	34	(12)	23	(8)
Sanger and Phelps *(7)*, (N = 330)	110	(33)	141	(43)	52	(16)	27	(8)
This study, static question (N = 210)	62	(30)	91	(43)	40	(19)	17	(8)
This study, animated question (N = 210)	120	(57)	51	(24)	30	(14)	9	(4)

[a]The sum of all four choices and the total number of students are not the same; presumably, this is because some students left this question blank.

Table 2. Distribution of Student Responses to a Multiple-Choice, Particulate Representation Before and After Viewing an Animated Version of the Question

		Student Response Choices Made *Before* Viewing the Animation: Number Correct: A	Number Incorrect: B	Number Incorrect: C	Number Incorrect: D
Student Response Choices Made *After* Viewing the Animation	Number Correct: A	58	42	10	10
	Number Incorrect: B	3	41	6	1
	Number Incorrect: C	1	4	24	1
	Number Incorrect: D	0	4	0	5

Note: For statistical purposes, the data for (C) and (D) were collapsed into one group. The boxes around the data represent the 3 × 3 grid used for the McNemar test for significance of change.

frequencies for six of the cells in Table 2 were less than 5, we collapsed two of the categories (C and D) into one. The boxes around the data in this table show how the data were collapsed for the statistical analysis.

Animation Design

The primary goal in creating the animation was to animate the particle motions in the three distractors consistent with the way students *think* they are moving. The particle motions in the correct answer were governed by kinetic-molecular theory and not by the students' beliefs. Sanger and Phelps *(7)* provided a summary of students' beliefs regarding the particle motions in each picture, and we used this information to design the particle motions in each of the three distractors. The gas in this question was changed from hydrogen (H_2) to helium (He) so students would not be confused as to why diatomic hydrogen was being drawn as a single dot.

The first author storyboarded the five animation events (the initial picture and the four multiple-choice options) and created the computer animation using Director 8.5 for the Macintosh *(30).* In the initial picture, nine red circles representing He atoms were animated so that they moved in rapid, straight-line motions unless undergoing a collision with another He atom or the walls of the circular container; all four multiple-choice responses were animated with nine particles moving in straight-line motions (unless colliding with another He atom or the container walls), but moving slower than those in the first picture.

The correct answer (A) was animated so that the particles occupied the entire container and collided with the walls. Particles in option (B) were animated so that no particles ever moved more than half of the container's radius away from the center and no particles ever collided with the container walls; if the particles moved too far from the center, they turned around in mid-air. Particles in option (C) were animated so that they occupied the bottom portion of the container; if the particles moved too far up in the container, they turned around in mid-air. Particles in option (D) were animated so that no particles ever moved more than half of the container's radius away from the walls; if the particles moved too close to the center of the container, they turned around in mid-air.

After the animated question was created, we asked three Ph.D. chemistry faculty members to evaluate whether the question measures the proper chemistry content (i.e., assessing content validity). Each of the three faculty agreed that the initial picture and the correct option showed particle motion that is consistent with kinetic-molecular theory. The faculty also agreed that the other three distractors did not follow kinetic-molecular theory, but they would have to violate these rules in order for the distractors to match the choices in the static question.

Results of the Static and Animated Questions

The distributions of student responses to the static multiple-choice question (pretest) and the animated question (posttest) appear in Table 1. The values for the static question in this study are very similar to the distributions from other students who have answered the static question (Table 1) in other studies. These values show that the static question is very reliable, since students from four different universities over 20 years provided very similar responses *(7).*

Although incorrect option (B) was the most popular choice for the static question, the correct answer was the most popular choice for the animated question and the percentage of students choosing the correct answer increased from 30% to 57% after viewing the animation. Table 2 contains data showing how students' answers changed after viewing the animated question. The results of the McNemar test for significance of change ($\chi^2(3) = 51.1$, $p < .0001$) indicate that the changes in student choices were not randomly distributed. While 62 of the 210 students (30%) changed from an incorrect option to the correct answer, only 4 students (2%) changed from the correct answer to an incorrect option; 16 students (8%) changed their answer from one incorrect option to another. These results suggest that the animation was effective at helping students abandon incorrect options in favor of the correct answer.

The number of students whose answer did not change after viewing the animation were 58 (94%) for the correct answer (A), 41 (45%) for incorrect option (B), 24 (60%) for incorrect option (C), and 5 (29%) for incorrect option (D). The fact that very few students with the correct answer changed their answer demonstrates that the animation did not have any adverse effect on students who had already chosen the correct answer. It is likely that these students were already able to visualize a dynamic view of this static picture on their own and did not need assistance from the animation. This is supported by a previous study *(7),* which showed that 79% of students choosing the correct answer on the static question provided explanations free from misconceptions regarding particle movement or behavior. The animation did have a positive effect on students who originally chose an incorrect option: 42 students (46%) who originally chose (B), 10 students (25%) who originally chose (C), and 10 students (59%) who originally chose (D) changed their response to the correct answer after viewing the animation.

Evaluating the Threats to Validity

The animation led to a significant improvement in the number of students choosing the correct answer and a subsequent decrease in the number of students choosing each incorrect answer. We believe that this improvement was a result of improving the static question to minimize at least one of the three threats to the question's validity that were identified previously *(7).* To determine which (if any) of these threats have been minimized, we analyzed the students' responses to the free-response questions regarding particle motions that were different than they had expected and their reasons for choosing the option they did.

The Importance of Particle Motion

There are several pieces of evidence suggesting that students' responses to the question changed significantly as a result of seeing the particles motions depicted in the animation.

First, there are a number of students who stated that the particles' motions in one or more of the four options were different from what they had expected. Most of these differences demonstrate that the students were not interpreting the static pictures in the way the authors of the question had intended or the way most instructors believe they are. The most common comments from students were that they had expected the particles in the correct answer (A) to move at the same speed as the original picture (mentioned by 17 students), and that they had expected the particles in the incorrect options (B), (C), and (D) to occupy the entire volume of the container instead of staying in a smaller region of the container (mentioned by 15, 6, and 13 students, respectively). Of the 37 different students making these comments, 31 of them (84%) chose the correct answer after viewing the animated question. This implies that although these students may have had different expectations regarding particle motions, they were able to identify the correct motions once they actually saw the particles moving. Picture (D) was the most difficult picture for students to predict the particle motions, and 7 students thought these particles would move in circular motions around the tank while 3 students thought these particles would remain frozen to the container walls. These beliefs about particle motions were not identified in the previous study *(7)*.

Another way to test the effectiveness of the animated particle motions is to look at the responses of students who changed their answer from an incorrect option to the correct choice. Ignoring the 8 blank responses, there were 54 students who changed their response to the correct answer. After seeing the animation, 42 of them (78%) said (A) was the best choice because it depicted the particles occupying the entire volume of the container and 35 (65%) said that (A) was correct because it showed the particles moving slower. These responses show that students who changed their mind and picked the correct answer after seeing the animation based their choices on the visual information provided by the animated particle motions.

Finally, the following student quotes also demonstrate that students believed the visual information provided by the animation was vital to answering the question correctly.

> The animation shows *exactly* what the helium atoms do at −20 °C. With the animation you can see the atoms move slower but not moving closer together. The animation is a very good illustration.

> The animation better shows the speed at which the particles are moving, which I had not considered.

> B doesn't look how I expected. I didn't expect them to stay together the whole time. A shows how when they slow down they are still going to be far apart. Because when they get cooler, they slow down but don't come together.

> Yes, the animation [A] moved slower than the rest causing me to change my mind. My picture [A] is the best choice because when a temp is lowered, it slows down the rxn, so therefore the particles are still bumping into each other, just at a different rate.

There is very little evidence against the idea that the particle motions were important in changing students' responses to the question. Three students commented that (A) couldn't be the right choice because it looks the same as the initial picture. We had hoped these comments would disappear once students saw that the particles in (A) were moving slower than the original picture. Also, 11 students provided quotes showing that they had misinterpreted the purpose of showing particle motions. Each of these students stated that they chose their final choice because it depicted the particles moving the slowest. Interestingly, they did not all choose the same picture! One of them chose (A), four chose (B), four chose (C), and two chose (D) as the picture that showed the particles moving the slowest.

The Equivalence of Options (B) and (C)

While most chemistry instructors view option (B) as depicting a gas whose volume has decreased and (C) as depicting a gas sample that has liquefied or solidified, some students viewed (B) and (C) as equivalent pictures showing different cross-sections of the tank under the same conditions. Although the first author tried to animate option (B) as a gas and option (C) as a liquid, the particle motions in the two pictures still seem very similar. However, the animation does seem to have helped students see option (B) as a gas and option (C) as a liquid or solid. After an analysis of students' responses for any mention of liquids or solids, we found 22 students claiming that (C) depicts a solid or liquid, and 7 students stating that (B) does not depict a solid or liquid, while only 1 student claimed that (B) represents a liquid. These results do seem to suggest that most students now view (B) and (C) as depicting different conditions.

The Possibility of Phase Changes

One way to eliminate the possibility of students incorrectly predicting the conditions under which helium gas would liquefy or solidify would be to give them the melting and boiling points of He under these conditions. The animation did not provide this information to students and did not attempt to address this threat directly (this is the goal of a future study that is currently underway in our group). Therefore, it is not surprising to find that students are still incorrectly assuming that He will turn into a liquid or solid at 3 atm and −20 °C. What is interesting is that a vast majority (29 out of 30, or 97%) of the students mentioning phase changes picked (C) as the option showing these changes. Research involving the static question *(7)* showed that (C) was preferred over (B) as a depiction of a liquid or solid sample by a margin of 3:1; that margin is about 30:1 with the animated question.

Conclusions

A sample of 210 students was asked to answer a static particulate-level question on gas properties (Figure 1) first used by Nurrenbern and Pickering *(1)*. After answering the static question, they viewed an animated version of the question and answered it again. For students who had answered the static question incorrectly, the animation was effective at helping them change their answer to the correct one. More students chose the correct answer for the animated question than for the static question (57% versus 30%, respectively), and for those students who did change their answers, more of them changed their answer from incorrect to correct (62 students) than vice versa (4 students). The animation did not have an adverse effect on students who answered the static question correctly, since 94% of them did not change their answer to an incorrect option.

We attributed the success of the animated question to the fact that the animated question has addressed at least some of the threats to the validity of the static question identified by Sanger and Phelps *(7)*. The major impact of the animation appears to be in minimizing the difficulty students have in visualizing the particle motions for each distractor. Analysis of students' comments indicated that several of them had conceptions of particle motion that were inconsistent with the motion intended by the authors and assumed by most chemistry faculty. As a result of viewing the animated question, most of those students (84%) chose the correct answer. The responses of students who changed from an incorrect option to the correct answer after viewing the animation showed that 78% of them chose the correct answer because the animation showed the particles occupying the entire container and 65% chose this answer because the animation showed that the only thing that changed was that the particles were moving slower.

The animated question also addressed another threat to validity of the static question: The fact that many students saw options (B) and (C) as being equivalent pictures that differed only in how the cross-section of the tank was cut. After viewing the animation, most of the students commenting about the gas sample turning into a liquid or solid referred to picture (C), and several students specifically commented that (B) does not depict a solid or liquid. While the animated question did not directly address the last threat to validity of the static question (the fact that students do not know the conditions required to liquefy or solidify helium gas), the animation did lead almost every student (97%) who described the possibility that helium would change states of matter to refer to option (C).

Note

1. The distractors in this question were changed so that there is the same number of particles in the initial drawing and each choice.

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