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Can Generating Representations Enhance Learning With Dynamic Visualizations?

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Abstract: This study explores the impact of asking middle school students to generate drawings of their ideas about chemical reactions on integrated understanding. Students explored atomic interactions during hydrogen combustion using a dynamic visualization. The generation group drew their ideas about how the reaction takes place at the molecular level. The interaction group conducted multiple experiments with the visualization by varying the amount of energy provided to ignite the reaction. The generation group integrated more ideas about chemical reactions and made more precise interpretations of the visualization than the interaction group. Embedded assessments show that generation motivated students to interpret the visualization carefully and led to more productive explanations about ideas represented in the dynamic visualization. In contrast, the interaction group was less successful in linking the visualization to underlying concepts and observable phenomena and wrote less detailed explanations. The study suggests that drawing is a promising way to help students interpret complex visualizations and integrate information.

Keywords: science education; curriculum development; inquiry

Learning chemistry involves understanding and linking representations at the molecular or submicroscopic (e.g., atomic interactions), symbolic (e.g., equations), and observable or macro (e.g., color change) levels (Gabel, 1998; Gilbert & Treagust, 2009; Johnstone, 1993). Students often have difficulty in understanding or making connections across representations (Keig & Rubba, 1993; Kozma, 2003; Nakhleh, Samarapungavan, & Saglam, 2005). For instance, many students understand chemical reactions solely as symbolic equations. They fail to link $2H_2 + O_2 \rightarrow 2H_2O$ with unseen processes such as atom arrangement, bond breaking, and bond formation (Krajcik, 1991). This study investigates the use of visualizations to promote robust understanding of chemical reactions by guiding students to link representations at the molecular, symbolic, and observable levels.

Dynamic visualizations offer great promises for science learning. They can make unseen processes visible such as molecular dynamics of chemical reactions. They can show coordinated changes in representations at observable, symbolic, and molecular levels. Students can integrate ideas by mapping their knowledge of one representation onto another (Seufert, 2003). Yet the impact of visualization on student learning remains controversial. Research syntheses report effect sizes for visualizations ranging from −1.5 to +2.3 in recent literature (Chang, Chiu, McElhaney, & Linn, unpublished data).

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To study these potential benefits we embed a dynamic visualization in an online inquiry-based curricular project using the Web-based Inquiry Science Environment (WISE, Linn & Hsi, 2000; Linn, Davis, & Bell, 2004). The guiding inquiry question is “Can hydrogen replace gasoline to power cars in the future? Why?” The project links a visualization showing atomic interactions during hydrogen combustion, the chemical reaction equation, and observable phenomena (explosion of a hydrogen balloon).

This research investigates the role of asking students to draw their ideas about chemical reactions to promote integrated understanding with the visualization. We compare two groups: students in the generation group draw their ideas about how the reaction takes place at the molecular level; and students in the interaction group conduct additional explorations of the visualization rather than drawing. The research questions addressed in this paper are:

- What is the impact of the Hydrogen Fuel Cell Cars curriculum on student learning?
- What is the impact of the drawing condition compared to the interaction condition?
- What is the impact of drawing on students with different prior knowledge?
- How does drawing help students integrate ideas from the visualization and link molecular, observable, and symbolic representations?

Rationale

Knowledge Integration Framework

Previous research documents that many factors contribute to the difficulty in building links between representations in chemistry learning. For instance, textbooks often emphasize symbolic representations and observable phenomena and present confusing images of chemical concepts at the molecular level (Ben-Zvi, Eylon, & Silberstein, 1987). Novice students often fail to establish correspondence between different representations (Kozma & Russell, 1997). Instructions often neglect everyday examples, making chemistry overly abstract.

To encourage the development of links among related scientific ideas, phenomena, and levels of representations, we use the knowledge integration framework to guide the design of the curriculum, assessment, and instructional comparison (Linn & Eylon, 2006; Linn et al., 2004; Varma, Husic, & Linn, 2008). The framework emphasizes connecting ideas from multiple perspectives. Students bring a wealth of perspectives about chemistry into science classes (Adadan, Trundle, & Irving, 2010). These come from everyday experiences such as igniting candles, sustaining camp fires, or mixing vinegar and baking soda. Some of these ideas are scientifically normative and coherent, while others are not. Research shows that instruction is effective when it provides ample opportunities for students to integrate their observations and link with prior knowledge through reflection and discussion (Linn et al., 2004).

Processes that encourage knowledge integration include eliciting student ideas (e.g., existing observations about hydrogen combustion), adding new ideas to build understanding (a molecular visualization of the chemical reaction), helping learners refine and sort their repertoire of ideas (asking for explanations about how the molecular view relates to their observations), and developing criteria for evaluating among ideas (asking students to draw the most important molecular reaction processes during hydrogen combustion) (Linn & Eylon, 2006). By engaging in these knowledge integration processes, students can see when their ideas conflict with each other and take an active role in refining their knowledge. Students who deliberately participate in these processes can develop lifelong learning skills. Our study focuses on how generating drawings can help students develop criteria to distinguish various ideas demonstrated in the visualization and promote integrated understanding of chemical reactions.

Challenges in Learning Chemical Reactions

For beginning students, making sense of a chemical reaction involves integrating a substantial number of concepts. To form a normative understanding of hydrogen combustion ($2H_2 + O_2 \rightarrow 2H_2O$), for example, students need to comprehend at least: (a) the structural aspects of chemical reactions, including the molecular structure of reactants and products (hydrogen gas, oxygen gas, and water); (b) the symbolic representations of H_2, O_2, H_2O, and $2H_2 + O_2 \rightarrow 2H_2O$, including coefficients, subscripts and conservation of matter; (c) the interactive nature of a chemical reaction, such as bond breaking and formation; and (d) observable phenomena associated with the reaction such as an explosion and fire (Ben-Zvi et al., 1987). They need to understand different types of representations to demonstrate the reaction at the macro, submicro, and symbolic levels and the triplet relationship among the representations (Gilbert & Treagust, 2009). An expert's understanding would include more complex information, such as the chain reaction process and conditions under which explosions would occur.

While expert chemists can move easily between different representations and understand relationship among representations, novice students find it challenging to understand chemical phenomena at the molecular or submicro level and link with other representations (Kozma, 2003; Kozma & Russell, 1997). For instance, students often believe that molecules and atoms have properties of macroscopic matters such as colors, weight, and temperature (Ben-Zvi, Eylon, & Silberstein, 1986; Margel, Eylon, & Scherz, 2008). Many learners think of chemical reactions as a static process rather than an interactive one (Ben-Zvi et al., 1987; Krajcik, 1991). They view chemical reactions as an additive equation without atom arrangement, bond breaking, or bond formation.

Such misunderstandings continue to occur throughout high school and college. Liu and Lesniak (2005) analyzed 6th, 8th, and 12th graders' performance on TIMSS items about chemical properties. They found little progress from 6th to 12th grade. Many grade 12 students hold the view that chemical reactions involve static processes, which is common among 8th graders.

Designing Dynamic Visualizations

Dynamic visualizations have great potentials to support chemistry learning. They can demonstrate dynamic unseen processes and offer a complete model of the processes. Compared to static visuals that use indicators such as arrows to symbolize temporal changes, dynamic visualizations bring temporal ideas to life and supports understanding (Park & Hopkins, 1993). Dynamic visualizations often employ multiple representations and support students forming integrated understanding in various ways (Ainsworth, 1999). For instance, multiple representations can complement learning by including pieces of information in each individual representation. By showing coordinated changes in multiple representations simultaneously, dynamic visualizations help students create referential connections between corresponding features of different representations with their knowledge of one representation mapped onto another (Seufert, 2003).

Visualizations have also been demonstrated to broaden participation in science. They offer new ways to represent complex problems and help connect ideas. Adding visualizations to instructions increase interest and insights in science (Boo & Watson, 2001). When asked what helps them learn science, two-thirds of 6th graders chose visualizations over explanations, reading, partners, and teachers (Corliss & Spitulnik, 2008).

Several studies have shown that visualizations improve the learning of different chemistry topics (Ardac & Akaygun, 2004; Barak & Dori, 2005; Frailich, Kesner, & Hofstein, 2009; Marbach-Ad, Rotbain, & Stavy, 2008; Sanger, Brecheisen, & Hynek, 2001; Williamson &

Abraham, 1995; Wu, Krajcik, & Soloway, 2001). Sanger et al. (2001) found that college students who viewed animations of diffusion of perfume molecules and osmosis of water molecules developed better understanding of random and constant movement of particles than those who did not. In Marbach-Ad et al. (2008) study, they found that dynamic visualization is especially a powerful tool to teach about dynamic processes. A study by Wu et al. (2001) found that visualizations not only improved learning but also affected how students interact with each other. Students who viewed molecular visualizations tended to discuss the molecular processes with peers as they were viewing the visualizations. Social interactions enable students to put complex observations into words and may contribute to improved understanding.

Yet researchers also warn that visualizations may not always be powerful. When learning with visualizations, learners are confronted with a number of challenging problems (Lowe, 1999). First, learners are faced with complex learning tasks. They need to understand the format and operators of each representation, the relation among representations, and how to the visualization relates to the target concept (Ainsworth, 1999). Without such knowledge, students may only see bouncing balls when we show them an atomic animation that is intended to vividly demonstrate an observable phenomenon like melting.

Second, visualizations may be cognitively overloading. The transitory nature of visualizations requires learners to keep more information in mind than is required with static visuals. Complex visualizations can overload memory and occlude key details (Ainsworth, 2006; Gilbert, 2007). Some animations may be too perplexing and have no advantage over static diagrams (Tversky, Morrison, & Betrancourt, 2002). In our study, we conducted pilot studies and refined the visualizations iteratively to reduce its complexity.

Third, visualizations can be deceptively clear. Some visualizations represent dynamic information in such an apparently simple way that learners may focus their attention on surface features and ignore conceptually relevant features (Cook, Wiebe, & Carter, 2008). They may become convinced they understand based on superficial observations (Chiu & Linn, in press). To address this issue, we designed a generation activity that requires students to draw their ideas after interacting with a visualization. The generation task encourages students to spend more time making sense of the visualization and analyze what they see.

Fourth, visualizations benefit from supportive curriculum materials that promote connections among ideas. Successful instruction with visualizations typically takes numerous cycles of refinement (Chang & Quintana, 2006; Clark & Doris, 2004). It often includes other activities and assessments that guide students to link visualizations and ideas (Frailich et al., 2009). For instance, the curriculum unit used in this study is designed following proven design patterns (Linn & Eylon, 2006), and employs embedded assessments to help develop links among representations. Students are guided to articulate their ideas, consider new ideas, distinguish among ideas, and reflect on their views. Carefully designed guidance encourages students to reconsider their ideas, to explain connections among molecular and everyday representations, to make productive links, and to resolve conflicts between ideas.

Generating Drawings to Promote Learning

To meet these challenges, we explored the approach of asking students to draw their interpretations of the visualization. After interacting with a visualization showing atomic interactions during hydrogen combustion, students were asked to create four or five drawings to represent molecular movement at different states of the reaction. This approach is built upon previous research on generation, modeling, learner-generated drawings, and desirable difficulties. It is expected to prompt students to realize gaps in their prior knowledge, revise their interpretations, and develop integrated understanding with the visualization.

Research on inventing drawings or representations suggests that generation promotes integration of new knowledge with prior ideas. Van Meter and Garner's study (2005) suggests that asking students to draw from an expository text helps them connect information in the text with prior knowledge. Rich and Black (1994) found asking students to draw their views before reading texts elicits students' background knowledge and promotes discussion. Asking them to draw their views after reading helps integrate ideas from the text with their prior knowledge. According to Chi's active–constructive–interactive framework (2009), drawing is an interactive learning activity, which can encourage students to recognize conflicts among ideas, examine these conflicts, and "self-repair" differences between ideas.

Other studies suggest that creating drawings helps because it involves reasoning across representations and written language. Ramadas (2009) reviewed previous research and found that creating and reasoning with diagrams or drawings often involves language-based reasoning. Learners reason across representations, texts, and oral languages, which encourages deeper understanding of the underlying idea. In a study asking students to invent graphs about speed and distance, diSessa, Hammer, Sherin, and Kolpakowski (1991) found that learners as a group used their invented graphs to explain real-life scenarios, realized flaws in their graphs, and discussed to revise their inventions. They advanced the understanding of the physics concepts through revision and discussion. One explanation to the success is representational competency (diSessa, 2004). Students drew on representational competency while evaluating and revising the graphs. As a result, representational competence becomes a resource for conceptual development.

Further, research on models and modeling supports the potential benefits of drawing. Creating drawings to model how hydrogen combustion takes place is a modeling practice and "involves students in the critical use of representations of all kinds" (Buckley, 2000:928). To create normative drawings, students need to represent not only bond breaking and formation, but also molecular structure of reactants and products. Moreover, learners need to consider the conservation of mass law and conserve the number of atoms in all drawings. To produce their own representations, students need to interact with prior knowledge about chemical reaction and the particulate nature of matter, and the information demonstrated in the visualization. Through drawing students engage in purposeful modeling practices and simultaneously advance their understanding of scientific concepts. It is unlikely that students create normative drawings without in-depth understanding of chemical reactions.

Another reason that generating drawings helps is that generation is a "desirable difficulty" (Bjork, 1994; Bjork & Linn, 2006). Psychology studies show that conditions that introduce difficulties to a learner may appear to slow down the rate of learning, but can enhance long-term retention and transfer of knowledge. Classroom studies show that generation compared to reading can promote knowledge integration (Richland, Bjork, Finley, & Linn, 2005).

In our research we expect that students can draw on their prior knowledge and representational competency to create the drawings. As a desirable difficulty, drawing functions as a testing and learning event that enables students to realize the gaps in their previous understanding about chemical reactions. Students are prompted to explore the visualization and integrate more ideas at the molecular level. Consistent with desirable difficulties, the drawing task may slow down learning but help students refine connections between ideas. Specifically, we hypothesize that:

- Generating drawings is better than interaction for helping students integrate ideas from visualizations.
- Drawing may have different impact on students with various ideas. For students who start with high levels of prior knowledge, generation may not have additional benefits compared to interaction.

- Drawing encourages students to realize gaps in their previous understanding about atomic interactions during chemical reactions. Students who draw will gather more precise information from the visualization than those who explore.

Instructional Materials

Hydrogen Fuel Cell Cars Project

The Hydrogen Fuel Cell Cars project was designed to help students form an integrated understanding of chemical reactions, which is a focus of middle school physical science curricula. According to the California Science Education Framework (2003), students should understand that ‘‘Chemical reactions are processes in which atoms are rearranged into different combinations of molecules.’’ Students should ‘‘know reactant atoms and molecules interact to form products with different chemical properties.’’ In addition, students are required to understand the particulate nature of reactants and products and to explain observable phenomena associated with chemical reactions.

This project illustrates chemical reactions within the context of hydrogen fuel cell cars. It starts by eliciting student ideas about whether gasoline powered cars will be replaced in the future, and then employs different representations to introduce chemical reactions, including a video of burning a hydrogen balloon, a visualization of hydrogen combustion at the molecular level, and a flash movie of the reaction inside hydrogen fuel cells. In the end, students participate in an online discussion on the advantages and disadvantages of the two cars. The discussion is designed to promote knowledge integration by offering students a chance to reflect and use the integrated ideas to construct their arguments. The activity sequence of the project with screenshots is laid out in Table S1.

The project employs proven design principles and patterns to promote links between scientific phenomena and representations (Linn & Eylon, 2006). For example, it uses the ‘‘explore-a-simulation’’ design pattern with embedded questions. One embedded question following the visualization of hydrogen combustion is ‘‘Is it safe to burn hydrogen inside the internal combustion engine as gasoline? Explain why.’’ This question requires students to connect molecular representations with everyday experience about car safety. The project follows the ‘‘making science accessible’’ principle of the knowledge integration framework (Linn et al., 2004). These patterns and principles guide interaction with the visualizations and prompt students to integrate ideas about chemical reactions.

Visualization of Hydrogen Combustion

This study focuses on helping students learn from the hydrogen combustion visualization embedded in Activity 2 (see Table S1 for the curricular activity sequence). The visualization shows how molecules and chemical bonds change during hydrogen combustion. It connects molecular and symbolic representations to foster integrated thinking about chemical reactions. It also features a ‘‘spark’’ button to control the amount of energy provided to ignite the reaction and a temperature bar to demonstrate synchronous changes in temperature. Figure 1 shows a screenshot of the visualization.

The visualization is developed using the Molecular Workbench software (Xie & Tinker, 2006), a powerful tool to visualize the collective motions of atoms and molecules. Each run of the software calculates Newtonian approximations of inter-atomic forces to decide how and where atoms will move and bond. By manipulating these highly descriptive visualizations of chemical reactions, students have the opportunity to develop a deeper conceptual understanding of the underlying chemical phenomena.

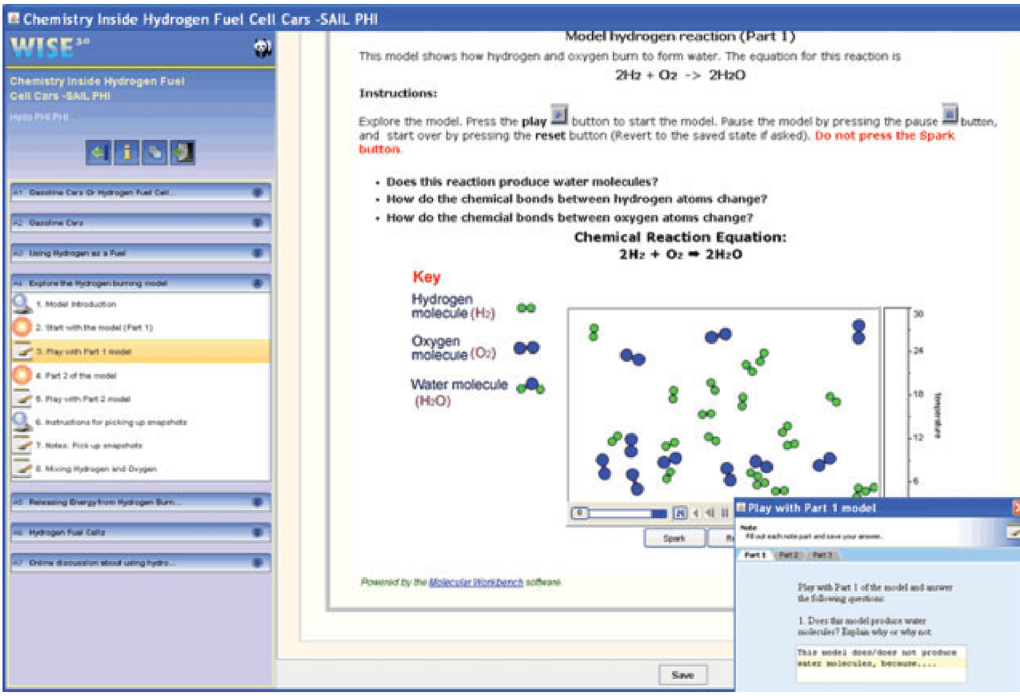


Figure 1. A screenshot of the Hydrogen Fuel Cell Cars project. Students use the map on the left to guide their inquiry, use visualizations within each step to help elicit and add ideas, and use pedagogical tools such as embedded notes to help refine their understanding about the visualizations.

The visualization possesses potentials to: (a) distinguish the dynamics of chemical reactions from static ideas (Ben-Zvi et al., 1987; Krajcik, 1991); (b) link molecular and symbolic representations of bond breaking and formation; and (c) foster links with observable phenomena by connecting to a video of hydrogen combustion in a balloon that students see earlier in the project.

Generating drawings supports learning by motivating students to distinguish various ideas about chemical reactions from the visualization. The task is designed to focus students' attention on molecular interactions and help integrate ideas of bond breaking and formation by linking with molecular representations.

Methods

Participants

Altogether 133 8th grade students from five physical science classes in a public school participated in this study. The school has a lower than state average for mobility (9% compared to the state average of 14%). Most of the students are Caucasians from working class families. The same teacher (Mr. H) taught all classes. He has 5 years of experience teaching middle school physical science and 3 years of teaching projects using the WISE. The WISE-targeted professional development program supported Mr. H when he was using the materials (Varma et al., 2008). All students had studied at least another WISE project before and were familiar with the WISE learning environment. The project was implemented after students had learned about the particulate nature of matter, but before any classroom instruction on chemical reactions. Mr. H taught both groups and students worked through the project in pairs.

Study Design

The five classes were randomly assigned to two groups: the generation group ($n = 81$, three classes) and the interaction group ($n = 52$, two classes). The two groups demonstrated similar levels of prior chemistry knowledge on the pretest [$t(131) = 0.16$, $p = 0.87$]. During this 6-day (a 50-minute period per day) project, both groups spent the first day registering for WISE, completing the pretest, and starting the project. By the end of the second day, all students finished the first half of Activity 2 and were about to start the visualization.

On the third day, students in the generation group explored the visualization, answered embedded questions, and generated paper-based drawings. Students were asked to create four or five drawings to represent interactions among three oxygen molecules and six hydrogen molecules before the reaction, right after the reaction starts, some time after the initiation of the reaction, and after the reaction completes. Because the visualization demonstrates such interactions dynamically with hundreds of frames and over 50 atoms, it is impossible for students to create correct drawings by simply copying the frames. Students need to interact with the visualization to integrate the ideas of bond breaking and formation with prior knowledge about particulate nature of matter, and apply the integrated ideas to create the drawings with the correct number of particles. In addition, we asked students to explain their drawings. The explanations can reveal supplementary information about what students draw. It is unlikely that students create correct drawings and explanations by copying expert views from the visualization.

Students in the interaction group explored the same visualization and answered the same embedded questions as the drawing group. Instead of being asked to generate drawings, they spent the extra time on the visualizations. Afterwards they were asked to explain how chemical bonds and molecules change during hydrogen combustion.

The teacher gave the same instructions to both groups, including asking to revisit the visualization, to make careful observations about how molecules and atoms move and chemical bonds change during each state of the reaction, and to revise their answers to embedded questions. Both groups finished these tasks within 40 minutes. For the next 3 days, all students worked on the remaining curricular activities embedded in the project. They finished the project and completed a posttest at the end of the sixth day. Thus only activities on the third day differed for the two groups.

Classroom Observations

During this project, one of the authors (HZ) visited the classroom everyday to observe the project run and provide support to teachers and students. Each time after her visit, the researcher filled out a classroom observation form developed by the Technology Enhanced Learning in Science Center (TELS, Varma et al., 2008). The observation form was designed to collect information about student work with visualizations by asking questions such as ‘‘What kinds of questions about the visualization do student pairs talk to each other?’’ and ‘‘How do students work with the drawing activity and the visualization?’’

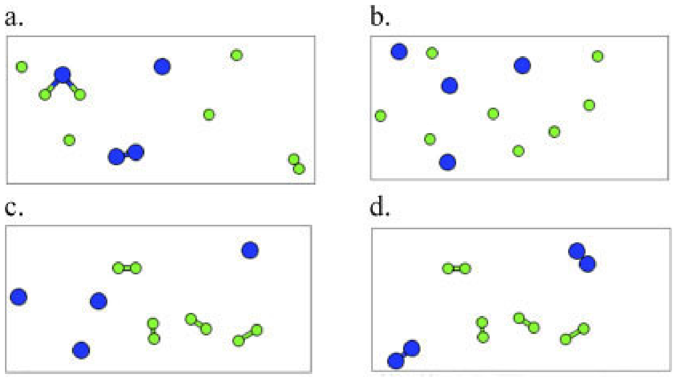
Assessments

The teacher administered identical paper-based tests to individual students before and after the project. The tests consist of five items and examined links between molecular and symbolic representations for bond breaking and formation. These items include two recognition items and three generation items. The recognition items ask students to identify correct molecular representations of chemicals before and after hydrogen combustion (see Table 1 for an example of the recognition items). Students need to make selections and explain their reasoning. The

Table 1

One item from the pretest and posttest, the knowledge integration scoring rubric designed for this item, and student sample answers

The following pictures are snapshots of particles at different time during the burning of hydrogen. A green circle represents hydrogen atom, and a blue circle represents oxygen atom. Which snapshot shows the particles before the burning of hydrogen gas starts? Explain your answer.



Explanation scoring rubrics:

Score	Description	Sample Answers
4	**Complex** Elaborate two or more scientifically valid links among ideas relevant to the context. Links between the ideas that the reaction has not started, the process of breaking bonds has not happened, and energy.	"Before heat is added the hydrogen atoms are connected, moving slowly. When the hydrogen gas begins to burn, the temperature increases causing the hydrogen atoms to break apart and move faster. The oxygen atoms are also connected now, moving slowly."
3	**Basic** Elaborate a scientifically valid link between two correct ideas relevant to the context. Links between the ideas that H_2 and O_2 are bonded because the reaction has not started and the process of breaking bonds has not started.	"The reaction hasn't started, so the bonds between H_2 and O_2 are not broken yet. They are still hydrogen and oxygen molecules."
2	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context.	"No extra energy is added." "Both hydrogen and oxygen are found uncombined in nature, as are other elements."
1	**Incorrect idea/link** Incorrect ideas about chemical reaction or molecular movement, or fails to make correct links between chemical reaction process and molecular movement	"They started with separated atoms."
0	**No answer or off-task answer** Student writes some text, but it does not answer the question being answered.	"I don't know." "I guessed."

generation items ask students to generate drawings and explain how the reaction between carbon and oxygen gas occurs.

The drawings created by students in the generation group and explanations by those in the interaction group provide further evidence of student learning. Combining these data reveals detailed information about how students developed ideas through the project.

Scoring

Assessments were scored based on the knowledge integration framework (Linn et al., 2006). The knowledge integration scores range from 0 to 4. These scores reward students for using evidence to make complex links between ideas. Students can use evidence from the unit as well as their prior knowledge. Higher knowledge integration scores indicate more complex connections between ideas. Previous research shows that the knowledge Integration scoring rubric, compared to coding schemes used in TIMSS (correct vs. incorrect or correct vs. partial vs. incorrect), provides a more precise and sensitive measure for the development of students' ideas in science (Linn, Lee, Tinker, Husic, & Chiu, 2006). Table 1 shows one pre/posttest item, the knowledge integration scoring rubric designed for this item, and student sample answers. The question asks students to identify the correct molecular representation of chemicals before hydrogen combustion begins. To score high, students need to correctly connect the symbolic and molecular representations.

Data Analysis

We analyzed student learning about chemical reactions by comparing pretest and posttest scores using paired *t*-test analyses. To determine the effect of the treatment, we conducted a multiple linear regression analysis, using the mean pretest score and group as explanatory variables, and the mean posttest score as the outcome variable. We calculated the effect sizes between the means of the posttest scores across the treatments to indicate the size of the observed treatment effect.

To compare the effect of generation and interaction on students with different prior knowledge, we categorized students' prior ideas as represented on the pretest. ANCOVA analyses were conducted to compare the pretest–posttest performance of learners with each idea. Further, to understand how students developed their ideas, we examined the work completed by students during the project. We categorized the ideas represented on drawings created by students in the generation group and those demonstrated in explanations by learners in the interaction group. We calculated and compared the percentages of students holding each category of ideas.

Results and Discussion

Classroom Observations

Overall, the teacher implemented the project successfully in all classes. As outlined in Table S1, the difference in treatments occurred on the third day. On Day 3, both groups interacted with the visualization by varying the amount of energy provided to ignite the reaction and observing different atomic interactions. Afterwards each pair in the generation group drew five pictures to illustrate the reaction process.

Classroom observations of the generation group revealed that

- Students in the generation group conducted more discussions than those in the interaction group. Many student dyads discussed what ideas should be included in their drawings and how they should plan the sequence of the drawings.

- During the drawing activity, students in the generation group revisited the visualization to check ideas when there was a disagreement between student pairs.
- During the remaining 3 days of instructions, students in the generation group often returned to the visualization and revised their responses to embedded questions.

Observations of the interaction group showed that

- Compared to those in the generation group, students in the interaction group spent more time interacting with the visualization by changing the energy provided and observing temperature change. They also revised answers to embedded questions.
- Many students in the interaction group completed the third day's work 5 minutes earlier than those in the generation group.

Learning Gains of Generation and Interaction Groups

Overall Learning Gains. Paired *t*-test results show that all students benefited from the project (see Table 2 for the *t*-test results). Students in both groups started with comparable levels of prior chemistry knowledge and made significant progress in understanding chemical reactions after the project. On average they had non-normative ideas about chemical reactions on the pretest and progressed to normative ideas on the posttest.

On the posttest, students in the generation group demonstrated more complex ideas and links about chemical reactions than those in the interaction group. Most students in the generation group developed normative ideas about bond breaking and formation. More than 50% of students in this group made one or two normative links between the ideas and molecular representations. In contrast, students in the interaction group only developed normative ideas about bond breaking or formation. Only a few students were able to make correct links between such ideas and representations.

Compare Groups. Multiple regression results show that the generation group achieved significantly higher scores on the posttest than the interaction group, after controlling for pretest scores. There was an interaction between students' pretest score and treatment (see Figure 2). For students who had a pretest score below 2.18, generation was more effective than interaction. The difference between the effectiveness of generation and interaction is less significant for students who started the project with a score higher than 2.18. The result indicates that generation is more beneficial than interaction for students who started with wrong or partial ideas about chemical reactions. The treatments are equally effective for students with higher pretest scores.

Learning of Students With Various Prior Ideas

To investigate the impact of generation on students with different prior knowledge, we categorized various initial ideas held by students and tracked how the ideas changed on the

Table 2
t-Test analysis results of both groups' performance on pre- and posttests

		Pretest		Posttest			
	N	Mean	*SD*	Mean	*SD*	Effect Size	*p*-Value
All students	133	1.30	0.65	2.33	0.58	1.58	<0.0001
Generation group	81	1.31	0.61	2.44	0.48	1.74	<0.0001
Interaction group	52	1.29	0.73	2.15	0.67	1.39	<0.0001

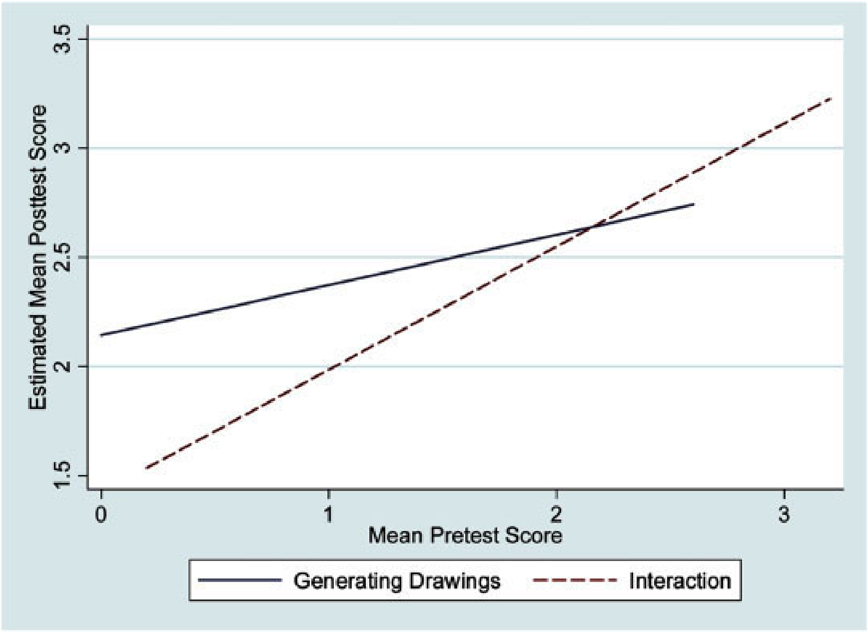


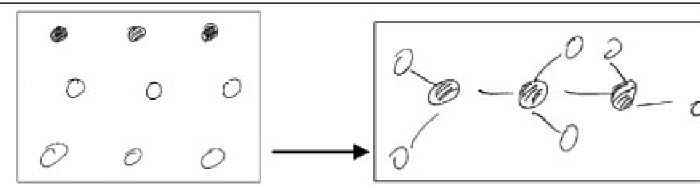
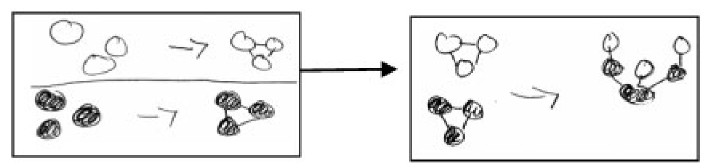
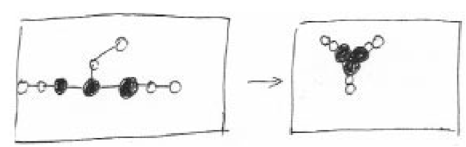
Figure 2. The estimated regression line of the two groups' performance from pretest to posttest. The x-axis shows the mean pretest score, and the y-axis shows the estimated mean posttest score. The multiple linear regression analysis was performed using the mean pretest score and treatment as explanatory variables, and the mean posttest score as response variable. There was an interaction between the mean pretest score and group. The estimated coefficient of drawing was 0.72 [$t(129) = 3.79$, $p < 0.001$], and the coefficient of interaction was -0.33 [$t(129) = -2.56$, $p = 0.01$]. The estimated regression equation was: Mean posttest score $= 1.42 + 0.56$ Mean pretest score $+ 0.72$ drawing $- 0.33$ Interaction.

posttest. We focused on students who had wrong or partial ideas before the project because drawing is more beneficial to them than interaction. Altogether 83 students expressed such ideas on the pretest (35 students, or 71%, from the interaction group and 48 students, or 61%, from the generation group). Their views include: the instantaneous view ($n = 56$), element view ($n = 13$), and chain view ($n = 14$). Table 3 presents description of these ideas with student sample drawings. Using the knowledge integration scoring rubric, these ideas were scored 1 on the pretest.

ANCOVA analyses were performed to investigate the effect of the treatment on these students with different ideas. Considering the large percentage of students holding the instantaneous view before the project, we next focused our analysis on the performance of these students.

Instantaneous View of Chemical Reactions. Fifty-six students (generation group: $n = 27$, interaction group: $n = 29$) held an instantaneous view about chemical reaction processes on the pretest. They believed that there were no intermediate phases during reactions. They typically drew two pictures to show how carbon burns at the molecular level, one showing the reactants and the other one representing products. They did not create any drawings about the intermediate phases during the reaction and viewed chemical reactions as an instantaneous process from reactants to products. One student, for example, explained the reaction occurs "like you have reactants, Bang! you get products. This whole thing is magic." Some students mentioned the term "molecular rearrangement" in their explanations, but their drawings did not represent dynamic processes of rearrangement such as bond breaking and formation.

Table 3
Students' alternative ideas about chemical reaction processes demonstrated on the pretest

Non-Normative Ideas	Description of the Ideas	Sample Answers to the Drawing Question That Asks to Draw How Carbon Burning Occurs	Knowledge Integration Analysis
Instantaneous view (total: $n = 56$, generation group: $n = 27$, interaction group: $n = 29$)	Chemical reaction is a static process. The reactants change directly to products, and there are no intermediate phases during a reaction	 "I think the carbons and oxygens will react to form the carbon dioxide. They will rearrange by themselves. There is nothing between (the reactants and products)"	Incorrect ideas about reactants and products. Non-normative links between symbolic and molecular representations for chemical reaction processes
Element view (total: $n = 13$, generation group: $n = 10$, interaction group: $n = 3$)	During the reaction, atoms first group by elements, and then different groups are connected to form one big molecule	 "All atoms are connected first, then they are connected to form a mega molecule"	Incorrect ideas about reactants, products, and chemical reaction processes
Chain view (total: $n = 14$, generation group: $n = 11$, interaction group: $n = 3$)	Before the reaction, atoms are connected as a chain. They rearrange and become a ring after the reaction	 "They (atoms) need to change from a chain to a ring"	Incorrect ideas about reactants, products, and chemical reaction processes

The ANCOVA analysis result shows that students who drew outperformed those who interacted on the posttest, after controlling for pretest score [$F(1, 53) = 10.12, p < 0.01$]. Students in the generation group achieved an average score of 2.64 on the posttest, while those in the interaction group had an average score of 2.04 after the unit. For students who had the instantaneous view before the project, generating drawings helped them integrate more ideas about chemical reaction processes from the visualization than spending more time interacting with it.

Element and Chain Views. A small number of students demonstrated other non-normative ideas about chemical reactions on the pretest. Students with element view ($n = 13$) drew reaction processes as atoms of the same element first forming teams, and then different teams connecting to form a gigantic molecule. Students with chain views ($n = 14$) represented all atoms being connected before and after the reaction. During the reaction the atoms change the way they connect. They may be connected as a chain before and form a ring after the reaction.

Students with element or chain ideas all developed correct ideas about bond breaking and formation on the posttest. The ANCOVA analyses results show that students benefited similarly from generation and interaction [element view: $F(1, 10) = 0.04, p = 0.85$; chain view: $F(1, 11) = 3.20, p = 0.10$].

In summary, these results show that all students benefited from the project. Drawing helped students integrate more ideas from the visualization than interaction. Students who had instantaneous view about chemical reactions, in particular, benefited more from generation than interaction. Considering the large percentage of students holding this ideas on the pretest, this helps clarify why generation overall is more beneficial than interaction. For students who started with higher levels of prior knowledge or other non-normative ideas, generation and interaction had similar impact on promoting knowledge integration from visualizations.

Knowledge Integration Through Generation and Interaction

To further understand how and what ideas drawing helps students integrate from the visualization, we analyzed students' drawings and explanations about hydrogen combustion processes. In this section we focused on comparing ideas represented in the drawings created by the generation group with views demonstrated in the explanations created by students in the interaction group. The explanations provided by students in the generation group served as supplementary information to assist our analysis.

According to the numbers of new ideas integrated, we categorized the drawings and explanations into four levels. Table 4 presents the categories for drawings and explanations. Students who draw or explained at low level failed to integrate the correct ideas about bond breaking or formation. Responses at single process level indicate that learners were able to integrate only one idea about bond breaking or formation. Learners who drew or described the complete process integrated both ideas from the visualization. If students drew or explained at the complex process level, they integrated not only ideas about reaction processes but also other related concepts such as temperature change and chain reaction. Compared to students at other levels, they have integrated the most ideas and developed the most sophisticated understanding about chemical reactions.

We calculated the percentage of students with responses at each level (Figure 3). The categorization results show that most students (78%), after interacting with the visualization and creating drawings, were able to integrate at least ideas about bond breaking and formation. Some of them (30%) also paid attention to other features demonstrated in the visualization such as energy and conservation of matter, which were not emphasized in the instruction.

Table 4
Categories of drawings created by students in the generation group and explanations created by learners in the interaction group

Levels	Category of Drawings	Category of Explanations
Low	Drawings do not represent any changes in chemical bonds. They do not represent bond breaking or formation	Explanations do not describe any changes in chemical bonds. They do not address bond breaking or formation
Simple process	Represent bond breaking or bond formation correctly	Explain bond breaking or bond formation correctly
Complete process	Represent bond breaking and formation correctly (i.e., how hydrogen and oxygen molecules break bonds and how hydrogen and oxygen atoms form water molecules)	Explain bond breaking and formation correctly (i.e., how hydrogen and oxygen molecules break bonds and how hydrogen and oxygen atoms form water molecules)
Complex process	Represent not only bond breaking and formation, but also other related ideas correctly. Such ideas include: the conservation of matter (all drawings showing the same amount of atoms), activation energy (drawing a spark to indicate providing energy to start the reaction), and chain reaction (drawing one hydrogen and one oxygen atom forming bonds first, then another hydrogen atoms forming bonds with the oxygen atom)	Explain not only bond breaking and formation, but also other related ideas correctly. Such ideas include: the conservation of matter (there is no loss of atoms), activation energy (need a spark to provide energy to start the reaction), and chain reaction (first one hydrogen and one oxygen atom form one bond, then another hydrogen atoms forms a bond with the oxygen atom)

In contrast, 20 students (38.5%) in the interaction group did not pay attention to atomic interactions or changes in chemical bonds at all, even though they spent more time experimenting with the visualization. Other students ($n = 20$, 38.5%) noticed some of the changes, yet they were able to integrate one idea about bond breaking or formation. They often only focused on one idea and ignored the other. Only 10 students integrated both ideas. Very few of them ($n = 2$, 4%) were able to integrate bond breaking, formation, and other ideas such as energy or temperature change.

Overall, asking students to draw their ideas prompted them to integrate more ideas about reaction processes from the visualization. One explanation is that the generation task required learners to consider a chemical reaction before, during, and after completion. Students needed to articulate and represent their ideas. This provided an opportunity for learners to test and realize that their interpretations of the visualization were superficial and insufficient. Students were prompted to revise their previous understanding. The interaction task asked students to explain the reaction, but did not require them to articulate their ideas in the same fine detail as the generation activity. Even though students in the interaction group spent more time interacting, they still ignored key changes demonstrated in the visualization. The drawing task prompted learners to observe more carefully and integrate more ideas from the visualization.

Case Study

To characterize how drawing supports knowledge integration, we analyzed performance for a representative student from the generation group. Student A started with an instantaneous view of chemical reactions, the most common non-normative idea held by students starting the project. He was selected because about 60% of the students in the generation group who had the same prior

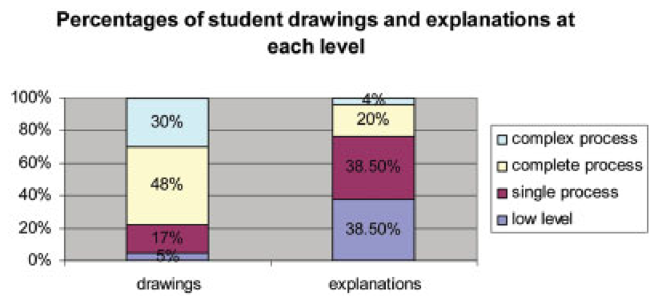


Figure 3. Categorization result of students' drawing and explanations about hydrogen combustion processes during the project.

knowledge ($n = 27$) achieved similar gains as A. The case tracks A's prior ideas, new ideas reconciled through drawing and interacting with the visualization, and ideas used on the posttest.

Pretest Performance. Student A started with an instantaneous view on the pretest (see Table 5 for student A's drawings and answers on the pretest and posttest). On the pretest, student A drew reactants as two groups: one group composed of three oxygen atoms and the other of three carbon atoms. He represented products as a gigantic molecule with all atoms grouped together. He explained the reaction as "once they (reactants) are put together, they rearrange to form a product. Basically, a start-finish process." He neglected intermediate phases and thought that reactants would manage to change directly to products after the reaction started. A's drawings reflect non-normative ideas about reactants, products, and reaction processes before the project.

During the Project. During the project A interacted with the dynamic visualization, answered embedded questions, and then started to draw. He initially explained hydrogen combustion as "when you hit the spark button, the temperature rises and it's hot enough to form a water molecule. The atoms go crazy from the temperature rising and they are ready to react." His explanation did not describe any changes in chemical bonds. This suggests that during A's first interaction with the visualization, he noticed how temperature controlled the reaction but did not attend to the changes of chemical bonds.

During drawing he was observed to re-explore the visualization. Altogether he generated five drawings to illustrate the reaction. The first drawing shows hydrogen and oxygen molecules correctly before the reaction; the second, the third, and the fourth drawings represent the formation of new bonds between oxygen and hydrogen molecules; and the fifth drawing demonstrated the formation of water molecules. He revised his explanations and explained the reaction as "(1st drawing) hydrogen and hydrogen bond, oxygen and oxygen bond before the reaction... (2nd drawing) Water molecules start forming, the oxygen atom is trying to bond with hydrogen atoms... (3rd drawing) Temperature goes up more and more movement. They are trying to bond with each other... (4th drawing) More bonds are formed between hydrogen and oxygen... (5th drawing) All the molecules are now water molecules. There is a lot of movement now." This shows that after drawing and revisiting the visualization A integrated the idea of oxygen and hydrogen forming bond with his prior idea about temperature change. He no longer attributed changes to the increase in temperature.

Consistent with our hypothesis, drawing prompts A to elaborate his idea that "atoms go crazy" and gather more information. He revisits the visualization for new information about interactions between specific atoms, reactants, and products. He integrates these new ideas in a way that extends his previous idea about the role of temperature. Yet student A does not

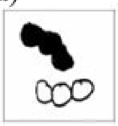
Table 5

Student A's drawings and explanations created in the drawing activity and answers to the pretest and posttest drawing item

Pretest drawing item:

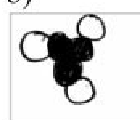
For the chemical reaction between carbon and oxygen gas, $C + O_2 \rightarrow CO_2$, imagine the reaction starts with three carbon atoms and three oxygen gas molecules. Draw pictures to show how the reaction happens. Use a black circle to represent a carbon atom and a white circle for an oxygen atom

a)



Explanation: "They are carbon and oxygen before the reaction"

b)

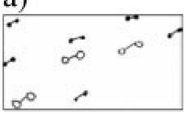


Explanation: "They all bond together after the reaction finishes. I think once they are put together, they rearrange to form a product. Basically, a start–finish process"

Drawing activity:

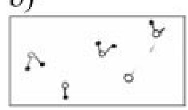
Based on what you have learned from the model, imagine you have a camera taking pictures during the burning of hydrogen. Draw pictures showing different stages during the reaction; explain how molecules change at each stage

a)



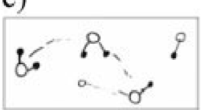
Explanation: "hydrogen and hydrogen bond, oxygen and oxygen bond before the reaction"

b)



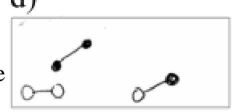
Explanation: "Water molecules start forming, the oxygen atom is trying to bond with hydrogen atoms"

c)



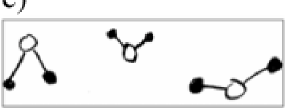
Explanation: "Temperature goes up more and more movement. They are trying to bond with each other"

d)



Explanation: "More bonds are formed between hydrogen and oxygen"

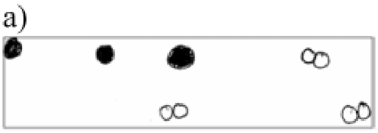
e)



Explanation: "All the molecules are now water molecules. There is a lot of movement now"

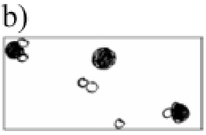
Posttest drawing item: (the same instruction as in the pretest)

a)



Explanation: "Before the reaction starts, the carbons have no bonds yet and the oxygens are bonded with another oxygen. Both are in their normal state"

b)



Explanation: "Bonds start breaking and the temperature rises (I made an educated guess). At the same time, some oxygen and carbon start bonding"

c)

Explanation: "New bonds are all formed and create carbon dioxide and the reaction completes" acknowledge the idea of breaking bonds nor does he connect bond breaking to temperature change.

Posttest Performance. On the posttest student A successfully applied these ideas to explain the burning of carbon. He drew three pictures and explained the reaction as "Before the reaction starts, the carbons have no bonds yet and the oxygens are bonded with another oxygen. Both are in their normal state. Then bonds start breaking and the temperature rises (I made an educated guess). At the same time, some oxygen and carbon start bonding. Finally, new bonds are all formed and create carbon dioxide and the reaction completes." This answer shows normative links between the ideas of bond formation and temperature change. Student A adds the new idea that bond breaking is part of the process. He links bond breaking and temperature change. Classroom observations noted that during the final 3 days of the project, A continued to re-explore the visualization frequently. He scrutinized the visualization and tracked the interaction between an oxygen atom and a hydrogen atom. This may have helped him integrate ideas about bond breaking. His revisit of the visualization demonstrates his realization that the visualization can help him refine his ideas.

In summary, student A initially viewed chemical reaction as an aggregation of atoms. The drawing task enabled him to recognize problems in his prior ideas and prompted him to revisit and observe the visualization carefully. Drawing functioned as a testing and learning event and helped him develop links between ideas and representations.

Conclusion

This study expands understanding effective uses of visualizations to help students gain integrated understanding of chemistry. Students learned chemical reactions by exploring a visualization embedded in an inquiry-based WISE curriculum project. This project was designed and iteratively refined using knowledge integration design patterns and principles developed in prior research (Kali, Linn, & Roseman, 2008). These patterns and principles characterize activities that help students use evidence to distinguish ideas and construct coherent arguments. The gains from pretest to posttest of both groups confirm the effectiveness of the design and the success of teaching chemistry with visualizations.

This research shows that the generation condition where students draw their ideas about chemical bonding can help them take full advantage of visualizations. Visualizations can be deceptively clear. When interacting with the visualization, students are exposed to enormous amount of information. They may have difficulty deciding what features are important (e.g., chemical bonding) and focus on details that are of less importance (e.g., the temperature change as student A). Meanwhile, they may not distinguish the non-normative ideas they bring to science class and the correct ideas observed in the visualization. As a result, many learners form superficial interpretations of the visualization and believe that they understand (Chiu & Linn, in press). The generation task requires learners to articulate and draw hydrogen combustion. To represent the visualization pictorially, students need to consider chemical bonding for certain number of atoms and molecules before, during, and after the reaction. Further they need to consider relevant concepts such as molecular structure and the conservation of matters law. Compared to interaction, generation provides more opportunities for learners to recognize conflicts between their prior knowledge and new views from the visualization. Students in the generation group integrated more ideas than did those in the interaction group. The case study of student A illustrates how the generation condition motivates learners to distinguish among the ideas they bring to science class and the ideas found in the visualization and helps them realize problems with their initial interpretations.

Drawing is especially helpful to students who have non-normative or partially correct ideas such as the instantaneous reaction idea. The drawing activity highlights the dynamic nature of a chemical reaction and provides an opportunity for students to add ideas about intermediate states. The generation task encourages them to re-explore the visualization. Drawing helps students refine general observations such as that the molecules "go crazy" or "want to bond" and to gather details about how the process occurs. The visualization adds ideas about chemical bond formation. Overall, students add ideas represented by the visualization, integrate these ideas into their prior knowledge, and distinguish ideas by generating drawings that use evidence from the visualizations. In their explanations they often reflect on how their ideas fit together. Therefore, drawing strengthens links between visualizations, symbolic representations, and underlying ideas about energy. It motivates students to revisit the visualizations and enables them to develop more coherent explanations.

Classroom observations of students working on the drawing activity resonate with this view. Before they started drawing, many students discussed the ideas in the visualization with their partners. They determined which ideas should be represented in their drawings. The drawing activity enabled them to generate drawings based on their interpretations and compare the drawings to the actions on the screen. The comparison helped them distinguish their interpretations from normative ideas supported by evidence from the visualization. In contrast, students in the interaction group with similar experiences were less likely to explain specific bond breaking and formation and use this evidence in their explanations.

Findings of this study have great implications for science educators and instructional designers. Dynamic visualizations provide new opportunities for students to make sense of scientific phenomena. Yet learners need guidance to effectively benefit from them. Generating drawings succeeds in enhancing student learning with visualizations. It focuses students' attention on key features of the visualization and engages them in knowledge integration processes such as adding, evaluating, and refining scientific ideas. To maximize their effects, it is crucial that visualizations are designed with surrounding instructional activities that can encourage such processes and prompt learners to revise their initial interpretations.

Limitations and Future Studies

Limitations of this study include that it is quasi-experimental because the teacher was recruited to participate instead of being randomly selected. The results may differ from situations involving participants, treatments, settings, and measures different from those in the study. This study measures immediate effects of the treatment using a posttest. Conducting a delayed posttest is a desirable future study and could clarify the long-term effects of generation and interaction on student understanding. Some of the assessment items (the generation item which asks students to draw and explain how the reaction of carbon combustion occurs) closely resemble the generation task during the curricular project. Students in the generation group may perform better on these items because they are more familiar with them than their peers in the interaction group.

Another limitation is that the instructions to students may differ across conditions. The instructions for the drawing task were intended to strengthen attention to the features of the visualization. By generating drawings, students needed to pay attention to atomic interactions. Although students in the interaction group were explicitly asked to explain atomic interactions, 20% of them ignored these instructions. It may be possible to design instructions for the interaction condition so that learners can increase attention to the atomic interactions.

In addition, the generation and interaction tasks are not isomorphic. The interaction task requires the explanation of the reaction process. The generation task includes careful consideration, articulation, and representation of the reaction for a certain number of atoms and molecules before, during, and after completion. It might be that careful articulation of the reaction also contributes to the effect of drawing.

Finally, research that includes analysis of student conversations during class could enhance understanding of the outcomes. Related research (e.g., Wu et al., 2001) shows that visualizations promote peer-discussions, which leads to improved learning. In the future we plan to investigate the impact of peer-discussion during generation and interaction. As noted, students were observed to spend time discussing and planning how to structure the drawings. Productive peer-discussion around the visualization may play an important role in supporting learning.

As our next step, we plan to refine our understanding of the mechanisms of drawing by incorporating student log data. Advances in technology make it possible to trace students' responses, actions, and interactions as they learn with visualizations. Logs of students' data can reveal the trajectory of learning and cognitive processes mediated by visualizations, and therefore can offer better guidance to improve learning. We plan to log students' interactions with the visualizations to gather information such as time spent on task, patterns of revisiting the visualization, and sequences for generating drawings.

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