Can a bridging visualization help chemistry students integrate observable and molecular views?

Research problem and objectives

Although chemists extensively use graphical representations to understand and communicate scientific ideas (Kozma et al., 2000), traditional chemistry education frequently neglects this visual-spatial aspect of chemistry especially for *molecular* views of chemical phenomena (Nyachwaya et al., 2011). For instance, despite many years of chemistry instruction, chemistry student teachers indicate many of the same alternative conceptions in their molecular-level drawings when compared to drawings by eighth-grade students (Calik & Ayas, 2005). Therefore this study investigates: how can computer visualizations best help students to connect chemical understanding across multiple spatial scales (e.g., at observable and molecular scales)? We hypothesize that a bridging visualization that combines observable and molecular views can help support these connections.

Rationale

Numerous studies have shown that, with appropriate scaffolding, computer visualizations can strengthen students' ability to depict and explain observable phenomena using molecular-level drawings (Ardac & Akaygun, 2004; Kelly & Jones, 2008; Sanger, 2000). However, many of these studies conceive of the "molecular" and "observable" views of chemical phenomena as wholly distinct (e.g., visualizations typically do not illustrate transitions between or intermediates of these two views). In contrast, we consider "molecular" and "observable" views to exist along a continuum; zooming in closely into a droplet of water (an observable view) would gradually yield a molecular view (molecules of water bouncing around). Kozma and Russell (1997) found that expert chemists were able to fluidly translate between multiple visual-spatial representations at different spatial scales; they called for instruction that could help students achieve a similar level of "representational competence" (see also Johnstone, 1993).

Hence, we extend previous research by investigating how *multiple computer visualizations at different spatial scales* can better scaffold the connections between observable and molecular views of complex chemical phenomena. We developed a one-week curricular unit named *Detergents* that focuses on (1) the chemical properties of detergent molecules and (2) how detergents were used to clean oil from birds endangered by oil spills. We selected this complex topic because it requires integrating understanding at multiple spatial scales such as: (1) the structure of individual detergent molecules, (2) how detergents form micelles, and (3) how detergents cause macroscopic change (e.g., how detergents can help dissolve oil). Consistent with the conference theme of "Non Satis Scire" and "serving the public good," we investigate how *Detergents* can foster student learning at a diverse, economically underserved high school.

Method

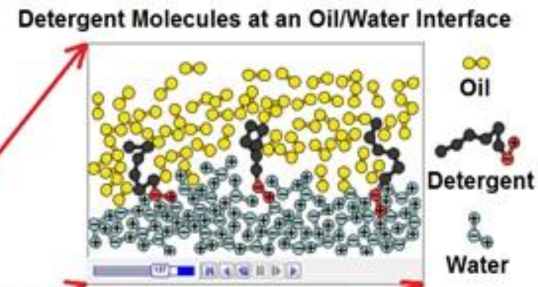
Participants

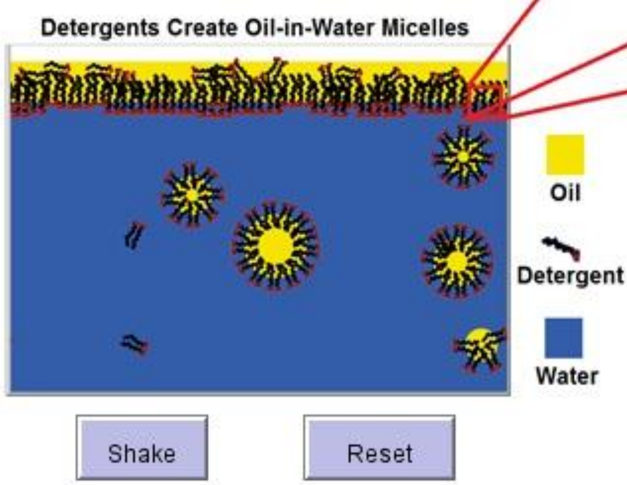
High school chemistry students (n = 107) studied *Detergents* at a culturally-diverse, low-income high school during the last month of the school year. At the school, 70% of students do not meet state science standards, 65% qualify for free or reduced lunch, and 25% are English language learners. Technology-enhanced inquiry learning is rare in the school's science curriculum. Students worked in dyads on the unit; a few unpaired students worked alone. Out of the five chemistry teachers that taught *Detergents*, only one teacher had used a previous version of *Detergents*.

Curriculum Materials

Detergents uses the compelling context of saving wildlife to help students make inherently difficult connections between standards-based topics of polarity, intermolecular attractions, and solubility (Sanger & Badger, 2001). Inquiry-based design principles helped guide the unit's development in the Web-based Inquiry Science Environment (Slotta & Linn, 2009; Linn & Eylon, 2011). Dynamic visualizations, developed by the Concord Consortium (www.concord.org), aim to help students coordinate molecular and observable views of detergents dispersing oil (see Figure 1). Our initial design showed micelles and individual water and oil molecules in the same visualization; pilot interviews revealed that learners found that visualization overwhelming and struggled to understand it. So instead, we introduced an intermediate "bridging" visualization that combines both observable and molecular views (Figure 1, left). This "bridging" approach mirrors Clement's (1993) use of bridging analogies to extend students' science understanding from one perspective to another.

Figure 1. The left screenshot shows detergents forming oil-in-water micelles. Students discover that the nonpolar tails of detergents attract oil molecules, and the polar heads attract water molecules. Before seeing this visualization, students argue what the structure of a detergent molecule should be, based on previous steps about polarity and intermolecular attractions.





The left bridging visualization combines observable components (oil and water are shown schematically; students can "shake" the mixture with the left button) whereas the right molecular visualization shows only individual molecules. Hence, the left bridging visualization aims to help students connect observable and molecular views of detergents dispersing oil.

Research design

To analyze learning from *Detergents*, we implemented a quasi-experimental cross-over design in which students in the *Detergents*-first condition (D1) studied *Detergents* (n = 3 teachers, n = 42 students) while students in the *Detergents*-second condition (D2) first studied a separate online chemistry unit (n = 2 teachers, n = 65 students). After completing this other unit, the D2 students then studied *Detergents* (see Figure 2). We administered drawing assessments at three time-points:

- **Time 1:** before students completed any online unit;
- **Time 2:** after students completed their first unit;
- **Time 3:** after the D2 students completed *Detergents*.

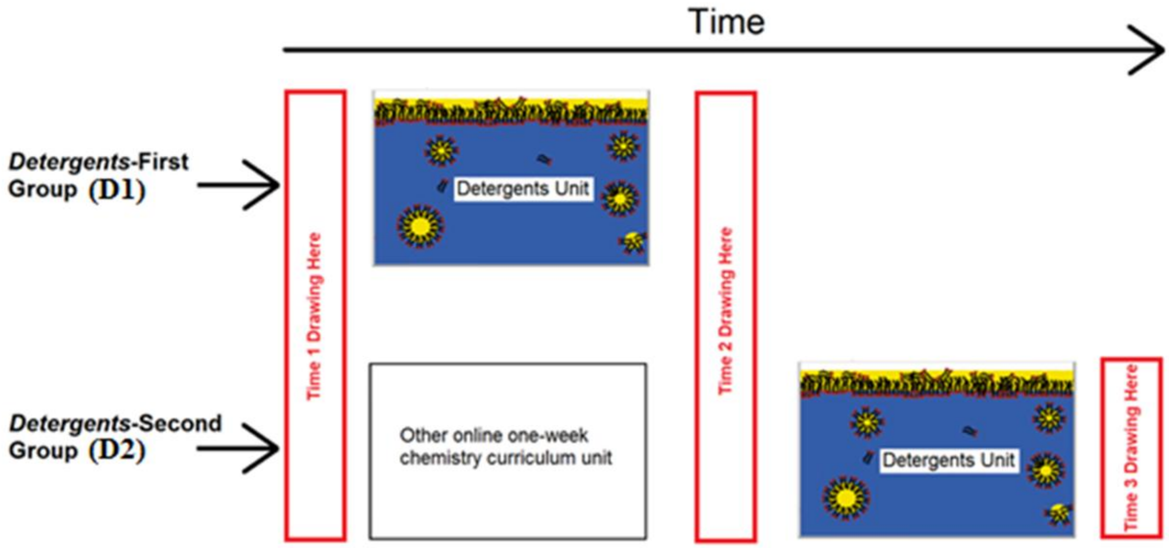


Figure 2. Diagram depicting the quasi-experimental cross-over design. The *Detergents*-first group (D1) completed *Detergents* first while the *Detergents*-second group (D2) completed another online chemistry unit before *Detergents*. Assessments were administered at three time points.

The strengths of this research design are two-fold:

- First, time 1 and time 2 drawings yield data for a controlled quasi-experimental design with an "experimental" group (D1) and "control" group (D2). The "control" group first completed a one-week unit that used computer visualizations to help students learn about the molecular structure of polymers and chemical bonding. In this way, the "control" group examines whether students make improvements from practice or from a comparable form of online chemistry instruction (that did not cover detergents topics).
- Second, we can analyze learning gains for the D2 group as well by comparing time 2 drawings with time 3 drawings. We predicted that only the D1 group would improve from time 1 to time 2 and that the D2 group would improve from time 2 to time 3.

Data sources

At each assessment time point, students were shown two observable-level pictures of an oil and water mixture (Figure 3, left) and oil, water, and detergent mixture (Figure 3, right) and then were instructed to "sketch how the oil, water, and detergent molecules would be arranged if you could see these two different mixtures with a powerful microscope."

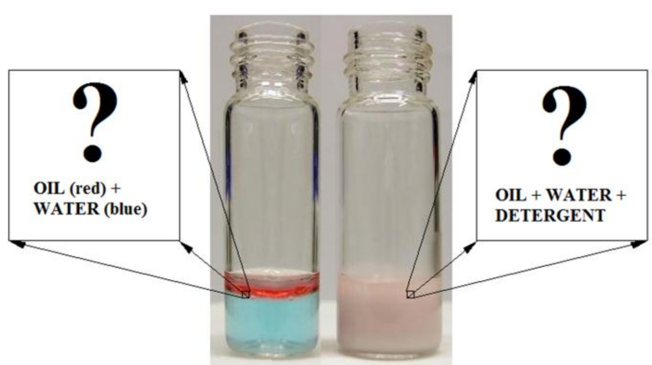


Figure 3. Students were shown this observable-level picture before asked to sketch a molecular-level drawing.

Each drawing was scored zero to four using knowledge integration rubrics (Liu et al., 2008) that measured how well students connected relevant scientific ideas in their drawings. These "relevant scientific ideas" were based on how students' drawings represented the (1) structure, (2) arrangement, and (3) polarity of oil, water, and detergent molecules. We summed scores on the oil/water drawing and oil/water/detergent drawing to yield a composite knowledge-integration drawing score.

Results

Student learning from *Detergents*

We first present quantitative results before presenting example student drawings in the next section. We first analyzed the time 1 to time 2 drawing scores, predicting that only students in D1 group would make significant improvements. As predicted, only students in the D1 group made large improvements from time 1 to time 2 ($t(41) = 6.03$, $p < .001$, $d = 1.00$), whereas students in the D2 group did not improve ($t(64) = 0.88$, $p = .38$, $d = 0.10$). Although the D2 group made no change from time 1 to time 2, change was significant from time 2 to time 3 ($t(64) = 5.64$, $p < .001$, $d = 0.86$) as predicted. We then compared the learning gains in the D1 group (time 2 score minus time 1 score) to the learning gains in the D2 group (3 score minus time 2 score). This analysis revealed no difference in learning gain scores between the groups ($t(105) = .22$, $p = .82$), indicating a robust effect of the *Detergents* instruction.

Students' molecular drawings

Figure 4 illustrates examples of two students' oil/water/detergent drawings before and after *Detergents* instruction (oil/water drawings are not presented for space considerations). Before instruction, student #1 represents a detergent molecule as a large central atom with three connected side atoms and randomly arranges detergent molecules relative to water and oil molecules. After instruction, the student changes the representation of detergent molecules and places them between oil and water molecules.

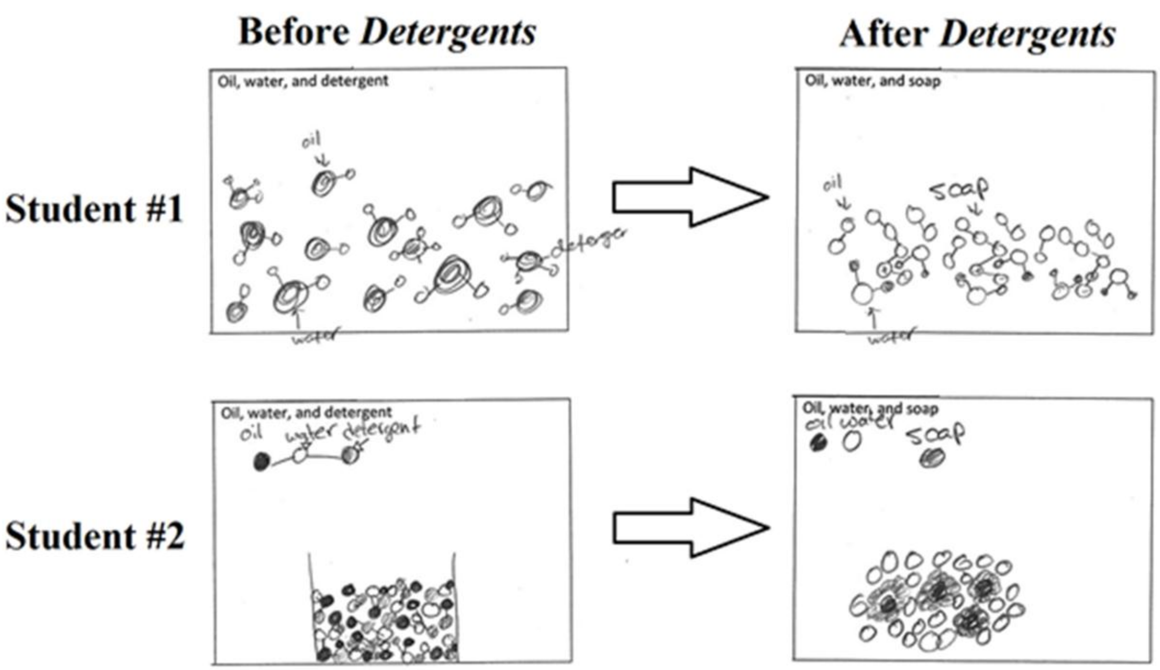


Figure 4. Oil/water/detergent drawings for two sample students before and after *Detergents* instruction.

More specifically, according to the knowledge integration rubrics developed for this drawing item, student #1 integrated three new normative ideas into the drawing after instruction:

- **Structure - Detergents have two different ends:** Drawing indicates that detergents have two qualitatively different ends (one end facing oil and one facing water)
- **Arrangement - Detergents are placed between oil and water:** Detergents are arranged at the boundary between oil and water molecules, which we interpret as progression toward understanding of micelles.
- **Polarity - Detergents are both polar and nonpolar:** Drawing indicates that detergents are both polar and nonpolar by the "+" and "-" symbols on one detergent end (the polar end) and the lack of these symbols on the other end (the nonpolar end).

Student #2 also shows improvements before and after instruction, but only on arrangement ideas; both drawings represent all molecules as single circles. According to the drawing rubric, student #2 integrated two new normative ideas after instruction:

- **Arrangement - Detergents are placed between oil and water.**
- **Arrangement - Detergents form oil-in-water micelles:** In *addition* to placing detergents between oil and water, the student also arranges the molecules into oil-in-water micelles.

Interestingly, the two students depict the behavior of detergents at different spatial scales. Student #1 appears to rely mainly on information presented in the molecular visualization (Figure 1, right) while neglecting micelle formation, illustrated by the bridging visualization (Figure 1, left). Conversely, student #2 ignores the atomic structure of individual molecules but illustrates the formation of micelles. Hence, although both students make important conceptual insights from *Detergents*, they do so in distinctly different ways.

While these example drawings help illustrate the rich, varied trajectories of improved learning outcomes, they are not meant to be representative of all students. Indeed, after instruction, only 13% of students drew oil-in-water micelles (like student #1) while 33% of students placed detergents between oil and water (like both students). For the detergents' representations, 21% of students drew detergents having two different ends (student #1) while 54% represented detergents as single circles (student #2). Interestingly, results revealed no correlation between sophistication in representing detergent molecules and arranging them. Students who drew micelles (student #2) or placed detergents between oil and water (both students) were no more likely to represent detergents as having two distinguished ends (both $\chi^2 < 1$, both $p > .30$).

Discussion

This study investigated how multiple computer visualizations at different spatial scales could help students understand and graphically represent observable phenomena at a molecular level. Students' drawings revealed that students seemed to rely upon the bridging visualization and molecular visualization to different degrees when making sense of how detergents function at the sub-macroscopic level. Students clearly struggled to fully integrate these two views as evidenced by the lack of correlation between the sophistication of the detergents' atomic structures and their molecular arrangements.

Although the curriculum and assessments were designed to be challenging, students nevertheless made large, robust improvements across multiple teachers. These results are particularly impressive given the fact that most teachers had not run *Detergents* in previous years and generally do not use computer visualizations in their typical instruction. This indicates that the design approach of using multiple visualizations to depict different spatial scales was successful in improving learning outcomes among a diverse, economically underserved student population. This study's results point to both the advantages and challenges of using such a bridging visualization to help students understand complex scientific phenomena at multiple spatial scales.

References

Ardac, D., & Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching*, *41*(4), 317-337.

Calik, M., & Ayas, A. (2005). A comparison of level of understanding of eighth-grade students and science student teachers related to selected chemistry concepts. *Journal of Research in Science Teaching*, *42*(6), 638-667.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, *30*(10), 1241-1257.

Johnstone, A.H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education*, *70*, 701–704.

Kelly, R. M., & Jones, L. K. (2008). Investigating students' ability to transfer ideas learned from molecular animations of the dissolution process. *Journal of Chemical Education*, *85*(2), 303-309.

Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *Journal of Learning Sciences*, *9*(2), 105-143.

Kozma, R.B. & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*, 949–968.

Linn, M. C., & Eylon, B.-S. (2011). *Science Learning and Instruction: Taking Advantage of Technology to Promote Knowledge Integration.* New York: Routledge.

Liu, O. L., Lee, H. S., Hofstetter, C., & Linn, M. C. (2008). Assessing knowledge integration in science: Construct, measures, and evidence. *Educational Assessment*, *13*(1), 1–23.

Nyachwaya, J.M., Abdi-Rizak Mohamed, A.-R., Roehrig, G.H., Wood, N.B., Kern, A.L., & Schneider, J.L. (2011). The development of an open-ended drawing tool: an alternative diagnostic tool for assessing students' understanding of the particulate nature of matter. *Chemistry Education Research and Practice*, *12*, 121-132.

Sanger, M.J. (2000). Using particulate drawings to determine and improve students' conceptions of pure substances and mixtures. *Journal of Chemical Education*, *77*, 762–766.

Sanger, M. J., & Badger, S. M. (2001). Using computer-based strategies to improve students' understanding of molecular polarity and miscibility. *Journal of Chemical Education*, *78*, 1412 - .

Slotta, J., & Linn, M. C. (2009). *WISE Science: Web-Based Inquiry in the Classroom*. New York, NY: Teachers College Press.