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Improving Representational Competence using Molecular Simulations Embedded in Inquiry Activities

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Abstract: The present article discusses the design and impact of computer-based visualization tools for supporting student learning and representational competence in science. Specifically, learning outcomes and student representation use are compared between eight secondary classrooms utilizing The Connected Chemistry Curriculum and eight secondary chemistry using lecture-based methods. Results from the quasi-experimental intervention indicate that the curriculum and accompanying visualization tool yield only small to modest gains in student achievement on summative assessments. Analysis of student representation use on pre- and post-assessments, however, indicate the students in Connected Chemistry classrooms are significantly more likely to use submicroscopic representations of chemical systems that are consistent with teacher and expert representation use. The affordances of visualization tools in inquiry activities to improve students' representational competence and conceptual understanding of content in the science classroom are discussed. © 2011 Wiley Periodicals, Inc. J Res Sci Teach 48: 1137–1158, 2011
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In typical physical science courses from middle school through university, students have difficulty coordinating their understanding of scientific phenomena and external representations of those phenomena (e.g., Mathewson, 1999; Rappoport & Ashkenazi, 2008). For example, students studying ideal gases rarely learn to move smoothly between macroscopic concepts (e.g., pressure, temperature) and mathematical expressions (e.g., the ideal gas law). More problematically, students struggle to explain how diagrams and illustrations of molecular interactions can be used to explain observed macroscopic phenomena and mathematical relationships. This difficulty in students' reasoning deserves particular attention because a component of scientific expertise is the ability to coordinate among different descriptions and representations of a given phenomenon and science instruction aims to help students increase their skills selecting the appropriate representations to communicate about macroscopic and microscopic phenomena (Kozma, Russell, Jones, Marx, & Davis, 1996).

Nowhere is the difficulty in interpreting and employing external representations to explain scientific concepts more prevalent than in chemistry. From their first course in

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chemistry, students must strive to understand chemical phenomena from multiple levels with multiple representations (Johnstone, 1993). As in other sciences, students come to chemistry with a wealth of ideas that are tied to their macroscopic experiences from everyday life, yet immediately they are asked to consider the identity and behavior of the submicroscopic particles that comprise matter. Chemists' and chemistry teachers' reliance on unique diagrammatic representations for communicating and teaching exacerbate the difficulty that students face connecting levels in chemistry. Because the interactions between the submicroscopic particles of interest in chemistry are imperceptible, chemists and chemistry teachers employ a host of symbols, such as chemical formulas, and other representations to depict submicroscopic objects and processes (Kozma & Russell, 1997). The wide range of representations available for representing any one submicroscopic object as well as the use of several mathematical and symbolic representations to represent macroscopic objects in chemistry pose significant challenges for the beginning student.

Challenges associated with selecting and interpreting representations have been identified as a significant problem to learning science in general and a primary barrier to learning chemistry (Johnstone, 1982, 1993). Although expert chemists switch fluidly among the symbolic, submicroscopic, and macroscopic levels and corresponding representations, students struggle to connect multiple levels and employ representations effectively throughout the chemistry curriculum (Banerjee, 1995). At the secondary level, where focused instruction in chemistry begins, students often fail to connect the representations displayed in curriculum materials with the appropriate descriptive level (c.f., Albanese & Vicentini, 1997; Ben-Zvi, Silberstein, & Mamlok, 1989; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993). Indeed, from their first chemistry course students are frequently seen to explain submicroscopic events using ideas and representations applicable only to the macroscopic world (Eylon, Ben-Zvi, & Silberstein, 1986).

Broadly, difficulties coordinating representations and levels can be attributed in part to students' meta-representational competence, or general skill "to select, produce and productively use representations" and "to critique and modify representations" (diSessa & Sherin, 2000, p. 386). Such skills are not unique to chemistry and rely on the body of knowledge that a student has about representations themselves and their utility for learning and problem solving (diSessa, Hammer, Sherin, & Kolpakowski, 1991). While this knowledge includes information about representations presented via instruction, it also encompasses students' intuitions about representations. Indeed, several studies have shown that students come to science classrooms with a wealth of ideas about the affordances of external representations that impact their performance in science (diSessa et al., 1991; diSessa & Sherin, 2000; Elby, 2000; Kohl & Finkelstein, 2006). Thus, interactions between individual differences in meta-representational competence and instruction about using representations in science may result in misinterpretations of canonical representations and domain concepts.

In chemistry, several researchers have identified student difficulties coordinating representations and levels with students' developing representational competence specific to the domain (Ardac & Akaygun, 2004; Kozma & Russell, 1997; Stieff & McCombs, 2006). From extensive analysis of expert practice working with multiple representations, Kozma and Russell proposed a comprehensive set of skills that define representational competence in chemistry. The authors note that these skills comprise students' ability to coordinate multiple chemical representations and apply unique representations for problem solving or for generating explanations of chemical phenomena. The authors identified five specific skills to target for chemistry instruction.

(1) The ability to identify and analyze features of a particular representation (such as a peak on a coordinate graph) and patterns of features (such as the shape of a line in a graph) and use them as evidence to support claims or to explain, draw inferences, and make predictions about relationships among chemical phenomena or concepts.
(2) The ability to transform one representation into another, to map features of one onto those of another, and to explain the relationship (such as mapping a peak on a graph with the end point of a reaction in a video and a maximum concentration in a molecular-level animation).
(3) The ability to generate or select an appropriate representation or set of representations to explain or warrant claims about relationships among chemical phenomena or concepts.
(4) The ability to explain why a particular representation or set of representations is more appropriate for a particular purpose than alternative representations.
(5) The ability to describe how different representations might say the same thing in different ways and how one representation might say something that cannot be said with another (Kozma & Russell, 1997, p. 964).

Although each of these skills refers specifically to the selection, interpretation or transformation of representations in chemistry, Kozma and Russell (1997) noted a correlation between these skills and students' conceptual understanding of chemical phenomena. Notably, individuals who displayed better representational competence were also able to produce better verbal descriptions of chemical principles relevant to the representations in tasks. This relationship has been observed in other instances. Stieff and McCombs (2006) observed that students who learn to use scientifically appropriate chemical representations produce more conceptually correct diagrams of chemical phenomena than students who use abstract or generic representations. Similarly, Coll and Treagust (2003) illustrated that students' conception of chemical bonding appears limited by their skill at selecting or constructing chemical representations from among the representations presented over several years of instruction. Such work suggests that the skills attributed to representational competence in chemistry by Kozma and Russell are tied closely to students' conceptual understanding in the domain and that instructional interventions that improve the skills that comprise representational competence may, in turn, improve students' understanding of chemical phenomena.

Using Computer-Based Visualization Tools to Improve Representational Competence

The present challenges surrounding students' representation use in chemistry has motivated novel approaches to designing curricular environments that improve student access to underlying concepts and build representational competence. Recently, design researchers have looked to computer-based visualization software as a promising tool with potential not only for improving general learning and achievement in science, but also for improving representational competence in chemistry specifically. Notably, computer-based visualization tools offer several unique advantages to learning chemistry in regard to the development of representational competence. Foremost, visualization tools support students' use of scientific representations to communicate. In chemistry, multi-representational visualizations of imperceptible objects and phenomena make explicit the information embedded in external representations with interactive visual displays (e.g., Russell et al., 1997; Stieff, 2005; Stieff & Wilensky, 2003; Wu, Krajcik, & Soloway, 2001). Embedded in inquiry-based curricula, such tools help students perceive the relationship between the representing and represented world. Using such tools in the classroom, students can improve their ability to accurately depict chemical phenomena as well as integrate their knowledge of scientific representations more systematically with content knowledge (Linn, Lee, Tinker, Husic, & Chiu, 2006; Stieff & McCombs, 2006).

The present paper reports on the on-going development and implementation of a computer-based guided-inquiry curriculum, The Connected Chemistry Curriculum, and its potential to support the development of representational competence in high school chemistry. The Connected Chemistry Curriculum utilizes simulations designed in Processing (Fry & Raes, 2001), NetLogo (Wilensky, 1999) and animations designed in Adobe® Flash to offer students direct access to the submicroscopic objects and phenomena under study in chemistry. As such, Connected Chemistry simulations teach chemistry from the perspective of emergent phenomena (Wilensky, 2001). That is, the simulations, embedded within inquiry activities, emphasize how the submicroscopic interactions between molecular objects result in macroscopic concepts and relate to symbolic representations used by chemists. Students can manipulate various parameters of Connected Chemistry simulations and animations to predict the outcome of reactions under study and receive instantaneous feedback from the visualization tool about the quality of their predictions. By facilitating the iterative process of observe-predict test, Connected Chemistry offers students with the opportunity to engage in the same processes of inquiry that characterize scientific practice.

Each unit in The Connected Chemistry Curriculum consists of three activities that support students' reasoning about the relationship between submicroscopic phenomena, symbolic representations and their experiences in the laboratory. In the *Laboratory/Demonstration Activity*, students perform a laboratory experiment in which they explore and observe macro-level chemical phenomena (e.g., volume, state of matter, descriptive characteristics). In the *Simulation Activity*, pairs of students explore a computer simulation to understand the nature of the submicroscopic interactions that are responsible for the macro-level events observed in the laboratory. Each pair completes a guided inquiry activity to explore the simulation, make predictions and generate explanations about the relationship between the submicroscopic and macroscopic world. In the *Discussion Activity*, the teacher leads students through a synthesis of their observations to discuss the conceptual underpinnings that link the submicroscopic interactions with their macro-level observations.

Figure 1 illustrates two screenshots from an animation on chemical reactivity and a simulation on states of matter. When completing each activity of a Connected Chemistry Curriculum unit, students are repeatedly invited to create and critique chemical

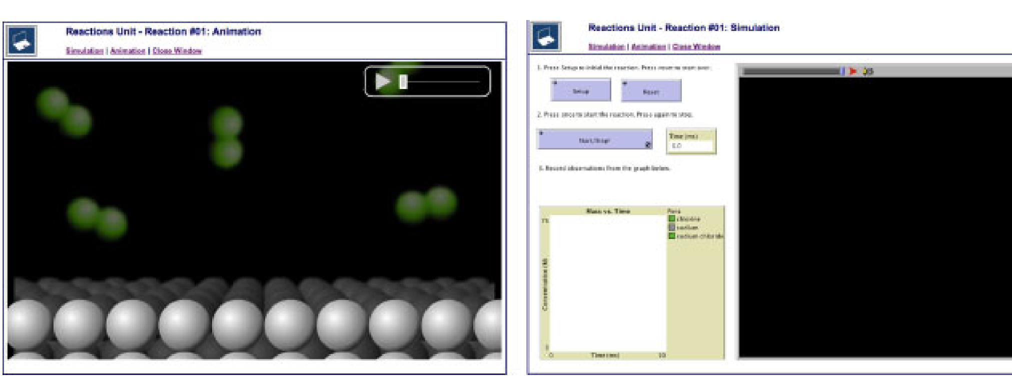

Figure 1. An example activity of the Connected Chemistry Curriculum *Discovering Matter!* Unit and accompanying Flash® animation and Netlogo simulation.

representations, such as those in the figure. They are asked to first observe and record the features of chemical and physical processes as they occur macroscopically in the laboratory. Using these observations, Connected Chemistry teachers ask students to conjecture about the molecular interactions that might explain their observations before exploring computer visualizations of the reactions that they are studying. Finally, the students, together with the teacher, compare the macroscopic and submicroscopic representations created over the course of the lesson and justify the use of each generated representation for explaining a particular aspect of the concept under study.

Previously, several studies have reported on the particular benefits of Connected Chemistry activities for improving student learning. Stieff and Wilensky (2003) documented how Connected Chemistry can help students clarify and strengthen their conceptual understanding of fundamental chemistry concepts, enhance students' ability to simulate macroscopic laboratory experiments, and support understanding of relationships between molecular interactions and chemical representations. In the classroom, Stieff and McCombs (2006) documented that students produce more detailed representations of chemical phenomena that are more conceptually accurate after using Connected Chemistry simulations. Similarly, Levy and Wilensky (2009a, b) observed that students learning via Connected Chemistry activities develop a better appreciation for the roles of models in chemistry and the affordances of external representations for communicating in science.

The results from these previous investigations suggest that Connected Chemistry activities may improve students' representational competence when embedded in a classroom curriculum. To that end, I explore the affordances of Connected Chemistry activities to improve student representational competence with respect to the third and fifth skills posited by Kozma and Russell (1997) while they learn about the particulate nature of matter. The design of each Connected Chemistry Curriculum simulation activity and accompanying teacher professional development materials specifically support students' developing ability to select the appropriate representation for explaining a chemical concept (skill 3) and to describe how unique representations can illustrate the same concept (skill 5). Consistent with the previous literature on the affordances of computer-based visualization tools in general and the specific affordances of Connected Chemistry, I examine four hypotheses in the present study.

First, students who complete Connected Chemistry activities will score higher on summative assessments of domain content than students who learn the same content without using Connected Chemistry activities. Previous studies have suggested that students who learn to use unique chemical representations for reasoning about specific concepts develop better conceptual understanding in chemistry (e.g., Kozma & Russell, 1997; Stieff & McCombs, 2006). If Connected Chemistry improves students' representational competence, it may in turn result in higher levels of achievement among students. Second, students who complete Connected Chemistry activities will employ submicroscopic chemical representations to describe chemical phenomena more often than students who learn the same content without using Connected Chemistry activities. Students are frequently seen to mistakenly employ representations and characteristics of macroscopic phenomena to explain the behavior of chemical phenomena despite teachers' emphasis on reasoning about submicroscopic phenomena (Erduran, 2005; Harrison & Treagust, 1996). Given the curriculum's emphasis on drawing submicroscopic representations of chemical phenomena and using them to reason about macroscopic observations, students who complete Connected Chemistry lessons should employ such representations more consistently and frequently to explain their reasoning than other students.

Third, students who complete Connected Chemistry activities will employ chemical representations consistent with chemistry practice more often than students who learn the same content without using Connected Chemistry activities. Connected Chemistry lessons consistently employ space-filling representations that are primarily employed by expert chemists and teachers to discuss concepts related to molecular motion and molecular interactions as opposed to generic representations (e.g., particle representations or ball and stick representations) or simple chemical formulas. Because the Connected Chemistry Curriculum employs space-filling representations consistently and Connected Chemistry teachers engage students in a dialogue about the best use of space-filling representations, students who complete Connected Chemistry lessons should employ space-filling representations more reliably. Fourth, students who complete Connected Chemistry activities will depict dynamic molecular motion in submicroscopic representations more often than students who learn the same content without using Connected Chemistry activities. Because students must frequently generate pictorial representations of Connected Chemistry simulations and animations that display the dynamic motion of chemical phenomena students, they are more likely to indicate their awareness that molecules are constantly in motion in their diagrams than students who learn about molecular motion from static representations alone.

I explore each of these hypotheses from an analysis of student performance before and after completing the Connected Chemistry *Discovering Matter!* Unit that teaches the concepts of the particulate nature of matter and state changes. Specifically, I compare the representation use of students who complete the *Discovering Matter!* Unit to students who learn the same content via lectures that employ static representations without the use of computer visualization tools. Differences in performance among students learning from each curriculum suggest that the *Discovering Matter!* Unit does not reliably improve the overall achievement of secondary students in chemistry, but it does result in significant improvements in students' representational competence. Ultimately, I posit that the students who complete Connected Chemistry activities display greater levels of representational competence and a more complete conceptual understanding after completing one Connected Chemistry unit early in a traditional chemistry curriculum and suggest implications for further development of Connected Chemistry units and other science curricula that employ extensive use of computer-based visualization tools.

Methods

Participants

Four hundred and sixty students and four chemistry teachers (three female, one male) participated in the study. Two hundred and thirty two students completed the Connected Chemistry *Discovering Matter!* Unit within the context of either a general or honors chemistry course at the secondary level. The remaining 228 students participated by learning the same topics covered in the Connected Chemistry Discovering Matter Unit within the context of either a general or honors chemistry course at the secondary level via lecture methods. The participant sample was approximately 49% male and 51% female. 81% were enrolled in 11th grade, 15% were enrolled in 12th grade, and 4% were enrolled in 10th grade at their respective high schools. As indicated in the analysis below, sample size varied as a function of item analysis, research question and data collection constraints.

Discovering Matter! was implemented and assessed in eight classrooms taught by four teachers at two different schools with largely different populations. First, Shadylane High is located in a middle-class urban community serving a primarily Asian and Latino student body and was ranked in the 7th decile statewide at the time of the study. The state Department of Education classified 72.2% of the students as "non-White" and 67.3% as receiving Free or Reduced Meals. Chemistry at Shadylane High was taught by Mr. Drake and Mrs. Damia. Mr. Drake, who had worked in a chemistry-related industry for 20 years prior to teaching, had taught chemistry for 13 years at the time of this study. Although each of his chemistry classes were titled "Regular Chemistry," Mr. Drake explained that all of his students were placed into his classes only if they had already completed pre-calculus and biology with a "B" grade or better. Mr. Drake emphasized the role of wet laboratory experiences and classroom demonstrations to engage students and enrich the chemistry learning experience. Mr. Drake arranged his classroom so that students worked independently, and he actively encouraged students to ask questions and share their understandings during demonstrations. Mrs. Damia had been teaching chemistry for 5 years at the time of this study. Her classes were titled "Chemistry," and she explained that students who were not placed in Mr. Drake's classes were assigned to her classes. She noted that the content and pace of her classrooms was necessarily more basic than Mr. Drake's to meet the needs of students with a history of poor achievement in math and science. Mrs. Damia expressed her belief that chemistry was one of the most difficult sciences for students with low math skills. She experienced frequent behavioral disruptions in her classroom, encouraged independent learning, and exerted considerable effort to keep her students focused on the learning activities at hand.

In contrast, Lakeview High is located in an affluent suburban community serving a primarily White student body and was ranked in the top decile (10th) statewide. At the time of observation, Lakeview had received the highest record AYP in the state, and both the teachers and students frequently commented on their achievement with pride. The state Department of Education classified 20.1% of the students as "non-White" and 32.5% as receiving Free or Reduced Meals. Chemistry at Lakeview High was taught by Mrs. Kraft and Mrs. Lida. Mrs. Lida had been teaching chemistry for 5 years prior to implementing Connected Chemistry. Each of her classes was titled "Chemistry," and she explained that her course was a bridge from earlier instruction in Basic Science to Honors chemistry or AP Chemistry. Mrs. Lida's students were second-year students who had completed one general physical science course. Mrs. Lida explained that her goal teaching chemistry was to excite students to study science and prepare them for future study in Mrs. Kraft's course. Her lessons included many examples of chemistry in everyday life as well as group activities. At the time of this study, Mrs. Kraft had taught Honors and AP Chemistry for 16 years (6 years at Lakeview High). She explained the majority of her students had taken Mrs. Lida's Integrated Science course and biology the year before and were enrolled in her advanced chemistry course to prepare for college. Ms. Kraft explained that her goal in chemistry was to prepare students for taking AP and SAT tests for college placement. Ms. Kraft emphasized the development of math skills in science and encouraged students to use models and collaborative problem solving in her class.

Procedure

Each of the four participating teachers attended 6 hours of professional development meetings to learn the goals of the Connected Chemistry Curriculum and pedagogical methods for implementing the *Discovering Matter!* Unit. Each teacher implemented the Unit in the context of the local school curriculum framework. Each classroom completed the Discovering Matter Unit over 180 minutes of classroom time; at Shadylane the Unit was completed in four 45-minute class periods, while at Lakeview the Unit was completed in two 90-minute "block" periods. During the implementation of the Unit, each teacher also covered the same content in two additional courses that did not use the *Discovering Matter!* Unit. In these courses, the teachers pursued the same learning objectives using lecture methods and textbook work over 180 minutes of classroom time; again this comprised four 45-minute class periods at Shadylane and two 90-minute periods at Lakeview. Student achievement and representation use was assessed using the *Discovering Matter! Unit Assessment.* All participating students completed the *Discovering Matter! Unit Assessment* on two occasions: 1 day prior to beginning the Unit and again 3 days after completing the Unit. All classrooms were observed and videotaped by the researcher and the assessments were scored by the author and an independent rater. Details of the Connected Chemistry intervention, the lecture intervention, and *Discovering Matter! Unit Assessment* are provided below.

The Connected Chemistry Curriculum Intervention. The *Discovering Matter! Unit* included three lessons that center on the use of molecular level simulations created in the NetLogo modeling environment. The content of the *Discovering Matter!* Unit includes regional standards-based concepts on the particulate nature of matter, physical and chemical changes, categorization of substances and mixtures and states of matter. These topics are typically covered early in a secondary chemistry curriculum and form the foundation of instruction in chemistry. In the activity, students classified elements, compounds and mixtures according to the composition and behavior of submicroscopic virtual particles presented via computer simulations and macroscopic laboratory observations. *Discovering Matter!* included one Laboratory Activity, three Simulation Activities, and one Discussion Activity that participating students completed in four 45-minute class sessions. In the 45-minute Laboratory Activity, students performed a standard laboratory experiment that involved recording the physical and chemical properties of different substances and separating various mixtures. In this activity, students were asked to consider the macroscopic properties of different substances directly.

The three Simulation Activities were completed in two 45-minute class sessions by pairs of students that explored Connected Chemistry simulations to understand the nature of the submicroscopic interactions that corresponded to their macroscopic observations. The first activity focused on observing the distinctions between different substances at the submicroscopic level, the second activity focused on observing the distinctions between different mixtures at the submicroscopic level and the third activity focused on observing the dynamics of chemical and physical changes (e.g., state changes) at the submicroscopic level. Importantly, the students were exposed to multiple representations of the phenomena under study in the unit. Each activity included illustrations of macroscopic substances, chemical formulas of those substances and space-filling diagrams of the submicroscopic compounds and elements in the simulations. In each activity, student pairs completed a guided inquiry exploration of the simulation that required them to make predictions about the composition and behavior of the submicroscopic particles that make up the substances they viewed in the laboratory and how they changed over time. Figure 2 illustrates an example question from the activity.

Notably, the activities required the students to engage iteratively in drawing macroscopic and submicroscopic representations of the relevant substances before, during and after they viewed the molecular simulation. Importantly, the Connected Chemistry Curriculum materials did not explicitly instruct students to communicate by using space-filling representations. Rather, students were only instructed to create drawings of their submicroscopic observations during the simulation activities using any representations they desired. In the 45-minute discussion activity, the teacher facilitated a debate about the classification and description of substances and underscored connections between observations made in the laboratory activity

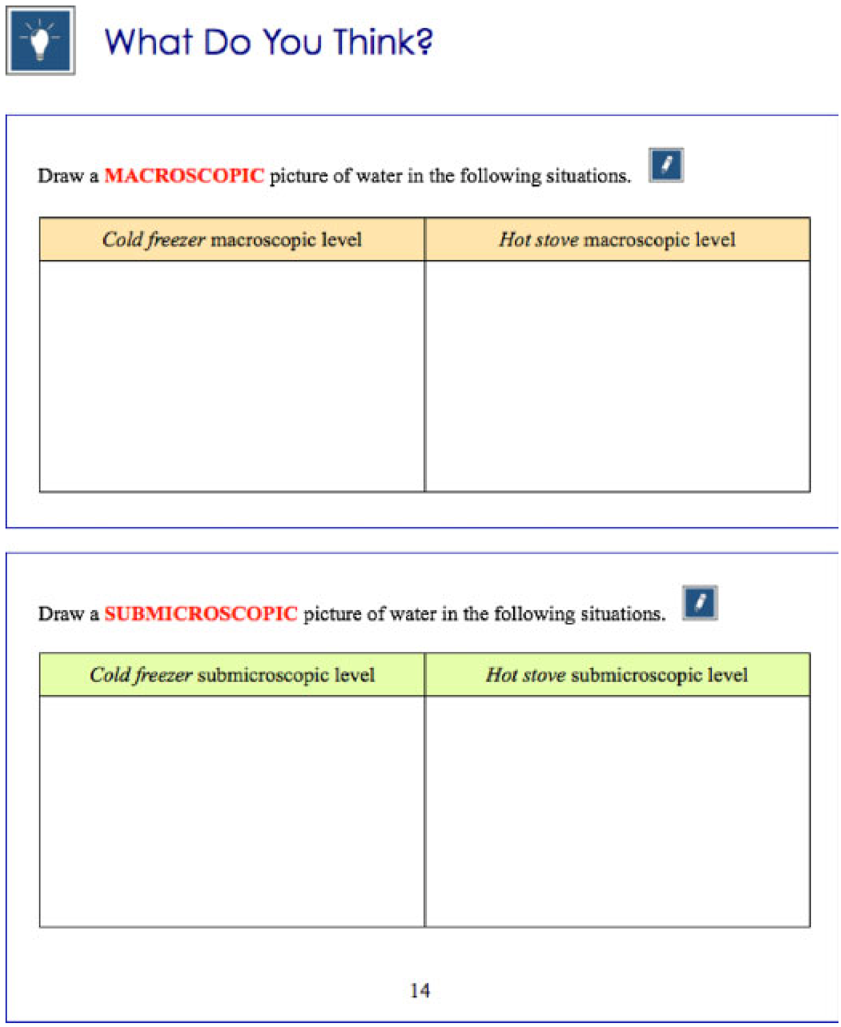

Figure 2. Discovering Matter! Activities ask students to draw submicroscopic representations, such as drawing diagrams of water molecules in the vapor phase and solid phase, before making observations of the molecular-level simulation.

and the Simulation Activity. In the discussion, each teacher guided students to reflect on their own and other students' observations to understand how macroscopic behavior emerges from molecular interactions, to compare their initial representations with their observations, and to consider how different representations are appropriate for making claims about different concepts they had explored.

The Lecture Intervention. The lecture-based interventions used by each teacher consisted of a formal lecture by each teacher that presented novel vocabulary with formal definitions (e.g., liquid phase, solution, solid phase) as well as individual problem solving by students. The teachers described the lecture methods as their "normal" pedagogical approach to teaching chemistry. In each classroom, the teacher remained at the front of the room (either seated or standing) and read from a list of notes individually prepared prior to class. Mrs. Kraft and Mrs. Lida each transcribed their notes onto a transparent slide that they projected on a white board in front of the classroom and asked the students to copy the transcription into notebooks. Mrs. Damia and Mr. Drake each transcribed their notes directly onto the whiteboard at the front of the classroom; they also asked the students to copy the transcription into notebooks. Lecture activities comprised one 45-minute class period in Mrs. Damia's and Mr. Drake's classes and one-half of a 90-minute block in Mrs. Kraft's and Mrs. Lida's classes. When introducing new ideas and terms, each teacher called upon individual students to explain what they knew about the topic and encouraged students to reflect on that students response. All four teachers strongly encouraged their students to interrupt the lectures if they had questions or if they wanted elaboration on an idea.

All four teachers assigned reading in the district-mandated textbook in class and as homework along with chapter-based problems to be completed individually. Collectively, these problems asked the students to provide formal definitions for vocabulary terms, classify samples (e.g., glass, river water, etc.) as mixtures, elements and compounds, and identify specific phenomena as chemical or physical changes (e.g., spoiling milk, boiling water, etc.). Each teacher devoted class time to reviewing the students' answers to each assigned problem and providing the correct answers from the textbook. Completion and review of homework materials comprised two 45-minute class periods in Mrs. Damia's and Mr. Drake's classes and one-half of a 90-minute block in Mrs. Kraft's and Mrs. Lida's classes. Students in the lecture classrooms also completed the same 45-minute Laboratory Activity as Connected Chemistry students in which recorded observations of physical and chemical properties of different substances and separated various mixtures.

In each classroom, the teacher employed macroscopic illustrations as well as symbolic and submicroscopic representations during their lecture presentations. Typically, macroscopic illustrations included drawings of generic liquids and solids, symbolic representations included chemical formulas, and submicroscopic representations included space-filling diagrams or generic particle diagrams. Notably, Mrs. Lida and Mrs. Kraft included a 45-minute modeling activity in which students worked in groups of four to create posters of submicroscopic representations of different substances. In the activity, the teachers provided each group with a list of three to four compounds and elements and asked the group to create a poster that illustrated how the compounds and elements should be represented on the molecular level and a storyboard that described state changes of water. The groups were allowed to work independently for approximately 30 minutes after which each group was allotted 5 minutes to display and explain their poster to the rest of the classroom. During the activity, each teacher circulated among the students to provide individual feedback on group progress before each group shared out their drawings. In contrast, Mr. Drake spent 30-minutes demonstrating state changes and mixtures in front of the classroom on day 2 and discussing the demonstrations with the classroom.

The Discovering Matter! Unit Assessment

Student learning and representational competence was assessed using the *Discovering Matter! Unit Assessment* (available as supplementary material accompanying the online article), which was developed by the author and the participating teachers specifically for the present study. The 13-item instrument included a variety of questions that asked students to define relevant terms, classify different types of matter and draw submicroscopic representations. Three items on the instrument are of particular interest to the present work and each is examined in detail below. Item 2 on the instrument asked students to draw a submicroscopic representation or either gold, air, or water. Item 7 asked students to generate a submicroscopic representation of a heterogeneous mixture and explain their drawing. Finally, item 10 asked students to generate three unique submicroscopic representations that depicted water as a solid, liquid, and vapor. Importantly, the summative assessments instructed students to draw pictures from the submicroscopic level, but no items indicated that space-filling representations must be used to provide an answer.

Student achievement on the instrument was determined using a standard rubric created by the researcher and participating teachers. The rubric was applied by the author and an independent researcher in two distinct phases. First, each item on the instrument was assigned a numerical score according to the rubric and a total score for the instrument (maximum 38) was calculated. Second, the researchers coded items that required students to generate submicroscopic representations (items 2, 7, and 10) according to the depicted level of the representation (submicroscopic or alternative); additionally, item 10 received a binary code according to whether dynamic motion was indicated in the student generated representation and verbal description. The assessments were rendered anonymous so that the researchers who applied the rubric were not aware of the related intervention. Comparison of the independent scores and codes yielded 98% agreement on 3,700 items. Disagreements were resolved uniformly by discussion.

Results

Student achievement on the *Discovering Matter! Unit Assessment* and student representation use on the items noted above were examined to address the stated research questions. Mrs. Damia was not able to administer post-test assessments to two of her classrooms and data was collected for only one Connected Chemistry course and one lecture course taught by Mrs. Damia. Below, changes in student achievement and representational competence after completing the Connected Chemistry Unit are examined within and between classrooms.

Effect of Connected Chemistry on Student Achievement

The first hypothesis of the study predicted that students who complete Connected Chemistry activities score higher on summative assessments of domain content than students who learn the same content without using Connected Chemistry activities. Although the positive effect of computer-based inquiry activities on student achievement has not been universally established (Kirschner, Sweller, & Clark, 2006), several studies suggest that positive gains are possible when the activities, such as those in the Connected Chemistry Curriculum, include significant scaffolding and explicit modeling of expert practice (e.g., Hickey et al., 1999; Geier et al., 2008). To address this hypothesis, the performance of students who completed the *Discovering Matter Unit!* (Connected Chemistry group) was compared to the performance of students who learned the same material via lecture methods (Lecture group) with a direct analysis of student pre-post achievement differences on the Discovering Matter Assessment. Specifically, the mean achievement score for each group on the post-administration of the assessment was compared via a 2 (curriculum) $\times$ 4 (teacher) ANCOVA controlling for pre-test score. Table 1 illustrates the average achievement on the assessment by teacher and curriculum.

Results of the analysis indicate a significant main-effect of curriculum, $F(1, 431) = 16.22$, $p < .001$. Average achievement on the post-test was greater for students in Connected Chemistry classrooms ($M = 24.1$, $SD = 6.1$) than for students in Lecture classrooms ($M = 22.6$, $SD = 6.0$).

Table 1
Average scores on at pre- and post-assessments

School	Teacher	Pre-Test N	Pre-Test Mean	Pre-Test SD	Post-Test N	Post-Test Mean	Post-Test SD
Lecture							
Lakeview	Kraft	67	19.1	5.9	67	26	4.3
	Lida	62	15.7	5.9	62	23.4	5.0
Shadylane	Drake	55	18.7	6.5	55	22.3	5.5
	Damia	30	13.2	4.5	30	14.5	4.4
Connected Chemistry							
Lakeview	Kraft	66	20	5.0	66	27	4.6
	Lida	59	14.1	6.5	59	21.7	5.4
Shadylane	Drake	69	16.8	6.3	69	25.9	5.1
	Damia	23	15	6	23	18.5	7.3

The overall gain in achievement between interventions was notably small (Cohen's $d = .25$). A main-effect of teacher was also observed in the dataset, $F(3,431) = 33.49$, $p < .001$. Mrs. Kraft's students scored highest on the post-test ($M = 26.2$, $SD = 4.4$), followed by Mr. Drake's students ($M = 24.3$, $SD = 5.4$), Mrs. Lida's students ($M = 22.4$, $SD = 5.2$) and Mrs. Damia's students ($M = 16$, $SD = 6.1$). A significant interaction was also noted in the dataset between curriculum and teacher, $F(3, 431) = 9.69$, $p < .001$), which revealed that the achievement gains from using the Connected Chemistry Discovering Matter unit was specific to two teachers. Planned post hoc comparisons for each teacher indicated that a significant main-effect of curriculum was localized to Mr. Drake's classroom ($F(1,124) = 31.55$, $p < .001$) and Mrs. Damia's classroom ($F(1,53) = 5.70$, $p < .05$). No significant differences were observed between Connected Chemistry classrooms and Lecture classrooms for either Mrs. Lida's or Mrs. Kraft's classrooms at Lakeview High School. While the analysis indicates that gains from using Connected Chemistry were not realized universally, the results illustrate that the curriculum holds potential to increase student achievement for some students on summative assessments of content knowledge.

Effect of Connected Chemistry on Level of Representation

The second hypothesis of the present study predicted that students who learn via Connected Chemistry activities use submicroscopic representations more often than students who learn the same content without using Connected Chemistry. Previously, Stieff and McCombs (2006) illustrated that Connected Chemistry students are more likely to employ submicroscopic representations, and a similar result was expected in the present study. To address this question, items 2, 7, and 10 were examined for representation use. As stated above, student inscriptions on these assessment items were coded according to their level of representation (macroscopic, microscopic, submicroscopic, and symbolic) as well as the type of representation used (particle, space-filling, and abstract). Examples of individual student work using each of these types of representations are displayed in Figure 3.

Several analyses were conducted to compare changes in student representation use on the three assessment items that required students to generate diagrams. First, the frequency of each level of representation used by all students was determined for each assessment (Table 2) and the number of submicroscopic representations employed on an assessment by each student was calculated (Table 3). A chi-square analysis was then conducted to compare the frequency of depicted levels and representations on pre- and post-tests between curricula.

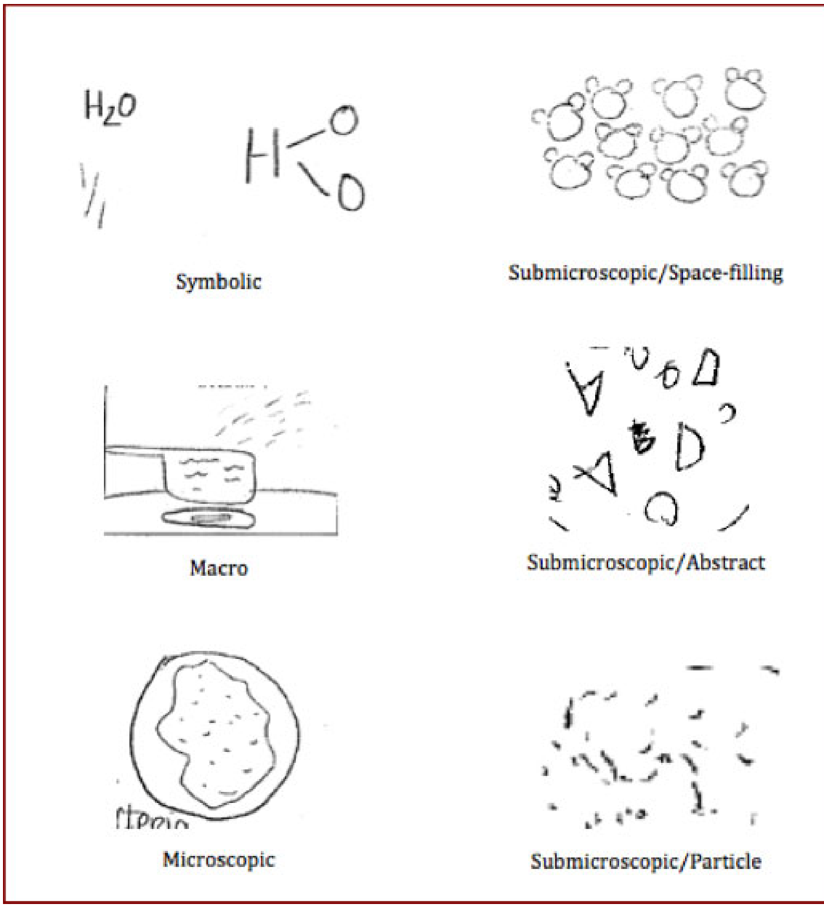

Figure 3. Examples of individual student inscriptions coded for illustrated level and for representation use.

Finally, the total number of space-filling submicroscopic representations generated on each test and in each curriculum was compared via chi-square. Analyses were conducted on both the aggregate level and for individual teachers. Identical trends were seen at both levels; therefore, the reporting of findings will focus on aggregate comparisons.

Table 2
Percentage of depicted levels by test and curriculum

	Pre-Test		Post-Test	
Level	Lecture ($N = 563$)	Connected Chemistry ($N = 549$)	Lecture ($N = 639$)	Connected Chemistry ($N = 655$)
Macroscopic	16	15	8	3
Microscopic	7	5	3	0
Submicroscopic	72	75	85	96
Symbolic	5	5	4	1

Table 3
Percentage of tasks on which students depicted submicroscopic representations

	Pre-Test		Post-Test	
Number of tasks	Lecture ($N = 219$)	Connected Chemistry ($N = 221$)	Lecture ($N = 221$)	Connected Chemistry ($N = 224$)
0	15	13	6	0
1	20	22	7	0
2	32	31	21	18
3	33	34	66	82

Comparison of the depicted levels of submicroscopic representation at pre-test indicated no significant difference in the frequency of levels of representation illustrated on each test, $z = .30$, $p = .76$. Students using each curriculum were equally likely to illustrate chemical phenomena from submicroscopic, macroscopic, symbolic and microscopic levels prior to instruction. At post-test significant differences were observed between curricula. Connected Chemistry students were seen to depict chemical phenomena from the submicroscopic level more frequently than students in Lecture classrooms, $z = .5.7$, $p < .001$. Chi-square analysis of the number of representations used at pre-test indicated that there were no significant differences in the use of submicroscopic representations between Connected Chemistry and Lecture students, $\chi^2(3,\ N = 440) = .77$, $p = .86$. Thus, students in each curriculum used submicroscopic representations with similar frequencies prior to the lesson. At post-test significant differences were observed. The analysis revealed that students in Connected Chemistry classrooms were more likely to respond to all three questions that required drawing using submicroscopic representations than students in lecture classrooms, Fischer's exact $\chi^2(3, N = 445) = 32.04$, $p < .001$.

Effect of Connected Chemistry on Representation Use

Student diagrams were analyzed further to test the third hypothesis that students who learn via Connected Chemistry activities will employ chemical representations consistent with chemistry practice more often than students who learn the same content without using Connected Chemistry activities. Although the previous analysis indicated Connected Chemistry students were more likely to use submicroscopic representations on their assessments, it did not indicate the type of submicroscopic representation used. Recall from Figure 1, submicroscopic diagrams were also coded according to whether the representation was space-filling, abstract or particle. Space-filling representations are used primarily by chemists and chemistry teachers to represent the composition and behavior of submicroscopic substances on the aggregate level particularly in secondary chemistry, and students worked exclusively with space-filling representations in each the three Connected Chemistry Simulation Activities included in *Discovering Matter!* Prior work has illustrated that students who work with a specific type of representation in the chemistry classroom develop a preference for using that representation (Copolo & Hounshell, 1995); therefore, similar preferences were expected for Connected Chemistry students. To test the hypothesis, items 2, 7, and 10 were analyzed specifically for the presence of submicroscopic space-filling representations. To analyze the use of such representations, each task received an additional binary code that indicated whether each student response depicted the relevant phenomenon using submicroscopic space-filling representations or with an alternative representation. Frequency counts of submicroscopic space-filling representations by curriculum

Table 4
Percentage of alternative and space-filling representations used by each group

	Pre-Test		Post-Test	
Representation	Lecture ($N = 403$)	Connected Chemistry ($N = 389$)	Lecture ($N = 420$)	Connected Chemistry ($N = 562$)
Alternative	39	35	19	4
Space-filling	61	65	81	96

and assessment are illustrated in Table 4. The total number of submicroscopic space-filling representations used by each student at each assessment is reported in Table 5.

Analysis of the pre-test tasks indicated no difference in the number of submicroscopic space-filling representation between the Lecture and Connected Chemistry students, $z = 1.31$, $p = .19$. Thus, both groups used these representations with similar frequency at the start of the school year. Likewise, no significant differences were seen in the number of submicroscopic space-filling representations used by each student at pre-test, $\chi^2(3, N = 263) = 3.32$, $p = .34$. At post-test, a proportionality test indicated that submicroscopic space-filling representations were present more frequently on Connected Chemistry assessments than Lecture student assessments, $z = 7.27$, $p \leq .001$. Likewise, Connected Chemistry students were seen to use submicroscopic space-filling representations to respond to all three task items more often than Lecture students, Fischer's exact $\chi^2(3, N = 260) = 44.7$, $p < .001$. Thus, Connected Chemistry students not only displayed a greater tendency to employ submicroscopic representations when asked to draw molecules, they were more likely to employ the same representations used by chemistry teachers and practicing chemists.

Effect of Connected Chemistry on Representation of Dynamism

The final hypothesis predicted that students who complete Connected Chemistry activities depict dynamic molecular motion in submicroscopic representations more often than students who learn the same content without using Connected Chemistry activities. Given that the students viewed simulations that displayed molecular motion over time in Connected Chemistry simulation activities, it is likely that they developed an appreciation for the dynamic motion of particles on the submicroscopic level than students who viewed static pictures in their texts and lectures. To answer this question the content of student responses to item 10 was analyzed specifically for any indication of dynamic motion. Note that item 10 required students to draw three illustrations of water molecules in liquid, solid, and vapor states. On the submicroscopic level, each state of matter for a given substance is characterized by the

Table 5
Percentage of space-filling representations used by each group

No. Space-Filling Reps	Pre-Test		Post-Test	
	Lecture ($N = 135$)	Connected Chemistry ($N = 128$)	Lecture ($N = 134$)	Connected Chemistry ($N = 126$)
0	32	28	19	2
1	33	26	22	7
2	21	30	43	44
3	14	16	16	46

relative distance of particles as well as the relative velocity of particles on the aggregate level. Typically, chemistry students are repeatedly seen to neglect the differences in dynamic motion or to inaccurately describe the relative velocity of particles when asked to explain differences between the three states of matter (Adadan, Irving, & Trundle, 2009). For example, students often claim that particles in solids do not move at all.

To determine whether Connected Chemistry students were more likely to indicate the unique differences in the dynamic motion of particles in each state, students' responses were assigned a single code that indicated whether dynamism was indicated in (i) the diagram, (ii) the verbal explanation, or (iii) both the diagram and the verbal explanation. Students were seen to represent dynamism in a variety of ways that ranged from diagrams that included velocity vectors and wavy "vibration" lines to verbal responses that stated the relative number of fast and slow molecules in each state. Each response received a final binary score indicating whether dynamism was represented or not represented regardless of representation. The frequency of each code in the dataset is illustrated in Table 6.

Chi-square analysis of codes applied to item 10 on the pre-test indicated no difference in the number of responses that attended to dynamic motion between the Lecture and Connected Chemistry students, $\chi^2(1, N = 323) = .28$, $p = .59$. Students in both groups were equally likely to note dynamic motion in some fashion prior to instruction. At post-test, chi-square analysis indicated that Connected Chemistry students illustrated dynamic motion in some manner more frequently than Lecture students, $\chi^2(1, N = 414) = 11.00$, $p < .001$. Averaged across the diagram and verbal responses, 52% of Lecture students had some indication of dynamism compared to 67% of Connected Chemistry students. Notably, Connected Chemistry students indicated dynamism in 91 diagrams while Lecture students indicated dynamism in only 31 diagrams. As illustrated in Figure 4, Connected Chemistry students frequently communicated their understanding that submicroscopic particles were in dynamic motion on the assessments.

Discussion and Implications

The present study aimed to identify the effect of the Connected Chemistry Curriculum on improving students' content knowledge as well as their representational competence in chemistry. Using a quasi-experimental design, chemistry achievement and representation use

Table 6
Students' depiction of dynamism on Item 10

	Pre-Test		Post-Test	
Depiction	Lecture ($N = 158$)	Connected Chemistry ($N = 165$)	Lecture ($N = 192$)	Connected Chemistry ($N = 222$)
Diagram	33	38	31	91
Verbal	9	5	25	20
Diagram & Verbal	19	16	43	39

	Pre-Test		Post-Test	
Depiction	Lecture ($N = 158$)	Connected Chemistry ($N = 165$)	Lecture ($N = 192$)	Connected Chemistry ($N = 222$)
Not depicted	97	106	93	72
Depicted	61	59	99	150

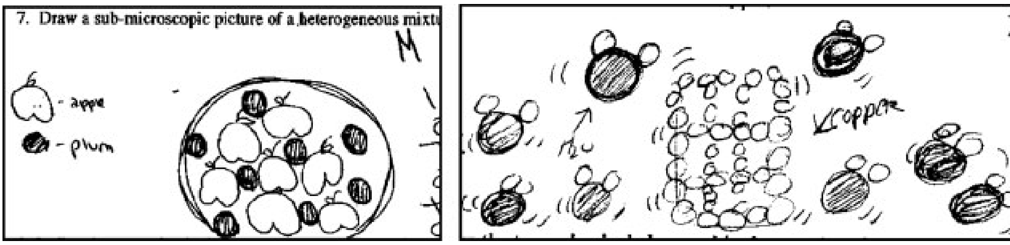

Figure 4. Student depictions of heterogeneous mixtures from a lecture classroom (left) and a submicroscopic Connected Chemistry classroom (right).

among high school chemistry students learning via the Connected Chemistry *Discovering Matter!* Unit was compared against chemistry achievement and representation use among high school chemistry students learning via lecture-based methods. Specifically, student responses on summative assessments regarding the particulate nature of matter were analyzed for conceptual accuracy, use of accepted submicroscopic representations and depiction of dynamic molecular motion. Generally, students who completed the Connected Chemistry unit displayed higher levels of achievement and more frequent use of submicroscopic chemical representations that illustrated dynamism than other students. The quality of student responses in Connected Chemistry classrooms indicated that the technology-infused curriculum is capable of improving both student achievement and representational competence in chemistry at the secondary level.

Comparison of student achievement gains between curriculum interventions suggests that the potential for Connected Chemistry, like any other curriculum, to improve student achievement is highly dependent upon local context. The curriculum was enacted in two different schools with four different teachers, and comparison of student achievement by teacher revealed that achievement in Connected Chemistry classrooms was greater than achievement in lecture-based classrooms in only one of the two high schools participating in the study. While it is possible that existing differences in students' prior knowledge at each school can explain the observed differences, no significant differences were seen between students at each school on pre-assessments. Rather, the results of the present study suggest that additional investigations are needed to determine how teachers' unique implementations of Connected Chemistry impact achievement and representation use among students with differing experiences.

The goals of the present study did not include characterizing implementation of the curriculum; however, daily observations of each teacher's lessons offer some potential explanation for the observed differences in achievement. Notably, Mr. Drake and Mrs. Damia at Shady Grove explicitly and repeatedly asked students to consider their macroscopic observations in the laboratory activity while they were working with NetLogo simulations in the simulation activity. In contrast, Mrs. Lida and Mrs. Kraft asked students to make careful observations during the simulation activity without reference to the laboratory activity. In addition, Mrs. Lida and Mrs. Kraft made extensive use of physical molecular models in their lecture courses: they displayed the models during their lectures and asked students to manipulate models while they reviewed textbook chapters. Although it is beyond the scope of this study to isolate the impact of each teacher's practice on their student's learning, the results clearly illustrate that the use of Connected Chemistry does not directly improve student achievement in all classrooms and alternative pedagogical approaches can be equally as effective.

Although large improvements in achievement were not observed in Connected Chemistry classrooms, there were significant improvements in representation use among all students who used the Connected Chemistry curriculum. Specifically, students in each of the seven analyzed Connected Chemistry classrooms employed submicroscopic representations more often than students in other classrooms when responding to assessment items that required depictions of molecular phenomena. Students in Connected Chemistry classrooms not only displayed a greater propensity for using submicroscopic representations, they also displayed a greater tendency to depict molecular phenomena using representations that were consistent with those employed by chemists and chemistry teachers. In all Connected Chemistry classrooms, students were seen to employ space-filling representations regularly to denote both the atomic composition and structure of molecules. This is in marked contrast to students in lecture classrooms who typically responded with symbolic representations or generic particle representations that did not illustrate composition or structure. Moreover, when responding to questions about submicroscopic behavior, Connected Chemistry students were seen to highlight the dynamic motion of molecules more frequently than lecture-based students. This result suggests that Connected Chemistry students developed a better understanding of the relationship between molecular motion and the physical properties of substances on the macroscopic level and attempted to illustrate those relationships consistently in their responses.

It is important to note that the instructional methods employed in the Connected Chemistry classroom differed significantly from the methods employed in the lecture-based classroom. Connected Chemistry activities systematically and repeatedly encouraged students to make predictions about the composition and behavior of submicroscopic phenomena, to communicate those predictions using submicroscopic drawings and to reflect on how those drawings correspond to both macroscopic observations and computer visualizations. Students in the lecture classrooms received many fewer opportunities to engage in viewing and drawing submicroscopic representations. As such, the benefits observed from the Connected Chemistry Curriculum should not be attributed solely to the use of visualization technologies in the classroom. The design of the present study prohibits isolating the observed differences to a single causal factor (e.g., use of technology, use of inquiry methods, opportunities for drawing). Rather, it is only possible to attribute the observed differences in achievement and representation use to the implementation of unique learning environments in the lecture-based and Connected Chemistry classrooms.

It is possible that the observed differences in achievement and representation use seen between the two learning environments may be due simply to the relative differences in the amount of content included in the lessons or the amount of time spent on drawing tasks. Daily observations of each classroom, however, suggest that these relative differences do not sufficiently explain the observed differences for two reasons. First, the chemistry content covered in each environment was not notably different: the researcher and the teachers agreed on the topics that would be included over the 4-day period and the teachers were not observed to include or exclude any topics in any classroom. Of note, although the same topics were included in both environments, the lecture-based classrooms devoted more time to lecture, group discussion and textbook readings that elaborated on those topics. Despite the lack of exposure to such elaborative activities, students in Connected Chemistry classrooms attained equivalent or better scores on the summative evaluation. Thus, the performance of the Connected Chemistry students is not likely due to additional coverage beyond that of the lecture courses.

Second, Connected Chemistry students did spend a proportionately greater amount of time engaged in drawing submicroscopic observations of molecular interactions than students in lecture-based classrooms; however, close examination of the classroom video and student assessments suggests the relative amount of time spent drawing cannot satisfactorily explain the variance in student performance. Discussions of the limitations of submicroscopic representations were present in the lecture-based courses, and the teachers were not exclusive in the use of drawing activities in the Connected Chemistry classrooms. In all classes, each teacher employed space-filling representations during the unit and discussed the appropriateness of different representations for communicating about different descriptive levels; however, each did so in very different ways and for different amounts of time. Of note, the teachers at Lakeview High School each implemented a 45-minute activity that involved students working in groups to create and discuss submicroscopic drawings that represented ideas presented from the earlier lectures. On days 3 and 4, these two teachers also drew space-filling representations on the whiteboard during class, required students to copy these representations into notebooks, and assigned textbook reading and worked problems that included space-filling representations. Despite the extensive use of submicroscopic space-filling representations by these two teachers, students in the Lakeview Connected Chemistry courses still employed submicroscopic space-filling representations more systematically and more accurately than lecture-based students on the summative assessment.

Despite these limitations, the results of the present study indicate that Connected Chemistry has significant potential to support students' developing representational competence in chemistry. Consistent with Kozma and Russell's (1997) third criterion of representation competence, Connected Chemistry students displayed an increased ability to employ scientifically appropriate submicroscopic representations to explain chemical phenomena included on the summative assessment. Students' representation use in Connected Chemistry is notable both for the tendency with which students strived to depict molecules from a submicroscopic perspective in addition to Connected Chemistry students' tendency to use scientific space-filling representations as opposed to idiosyncratic representations employed by lecture students. Similarly, Connected Chemistry students' were more likely to note differences in dynamic molecular motion and relative particle spacing between states of matter with both pictorial and verbal representations. This outcome suggests Connected Chemistry improved students ability to use different representations to explain similar aspects of chemical phenomenon, which is emphasized in Kozma and Russell's fifth criterion.

Moreover, the quality of Connected Chemistry students' drawings on post-assessments suggests the curriculum had a significant impact on students developing conceptual understanding of the particulate nature of matter. Students were not only seen to employ appropriate diagrams that noted the atomic composition and structure of molecules, they were also seen to indicate with great detail the relative motion of submicroscopic particles. Atomic composition is typically not discussed until later in the high school chemistry curriculum when empirical formulas are introduced and molecular motion is emphasized when kinetic molecular theory is taught even later in the traditional curriculum. Detailed drawings of the composition and dynamic motion on the post-assessments, such as repeating units of ionic compounds or the velocity of water molecules in ice, suggests that the curriculum and visualization tool helped students gain a more sophisticated understanding of the content early in the year. This finding is particularly interesting given that the assessments used in the present study involved the production of static diagrams: despite this Connected Chemistry students produced more representations of dynamic motions.

The present study is limited to demonstrating the impact of Connected Chemistry Curriculum activities on students' use of submicroscopic representations for communicating, and does not offer much insight into the character or function of the drawings students made. Elsewhere, Yip, Jaber, and Stieff (2011) have reported on preliminary semiotic analysis of student drawings obtained from Connected Chemistry Curriculum workbooks and summative assessments. In that work, the authors have illustrated that students who complete Connected Chemistry activities demonstrate an increasingly sophisticated ability to select and coordinate both verbal and pictorial representations to communicate their knowledge. Analysis of the students' drawings and written responses indicate that the curriculum catalyzes significant changes in students' understanding of how different representations can be used to represent knowledge for themselves and for others. Specifically, students in that analysis were seen to represent macroscopic properties and interactions using verbal modes of communication and to represent submicroscopic properties using particle and space-filling representations. Importantly, the analysis revealed that researchers themselves must coordinate both the words and the diagrams students employ in order to produce rich interpretations of student meaning-making in chemistry and other sciences.

In conclusion, the impact of the Connected Chemistry Curriculum on student achievement and representational competence in chemistry supports the growing literature on the general impact of educational technology on student learning in chemistry. Elsewhere, other tools have revealed that students are more likely to employ submicroscopic representations after learning with technology-infused activities. For example, Adadan et al. (2009) has recently illustrated that students are more likely to employ multiple representations to describe the particulate nature of matter after using a computer-based visualization tool compared to students who do not use such tools. Similarly, Yezierski and Birk (2006) have shown that computer animations are more likely to improve students' conceptual understanding of domain content than materials that present static illustrations of the same content. Ultimately, the convergent findings of these works suggest that innovative inquiry-based curricula that include significant use of computer-based visualization tools have significant potential to improve both student achievement and understanding in chemistry and other sciences (Linn et al., 2006).

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References

Adadan, E., Irving, K. E., & Trundle, K. C. (2009). Impacts of multi-representational instruction on high school students' conceptual understandings of the particulate nature of matter. International Journal of Science Education, 31(13), 1743–1775.

Albanese, A., & Vicentini, M. (1997). Why do we believe that an atom is colourless? Reflections about the teaching of the particle model. Science and Education, 6(3), 251–261.

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

Banerjee, A. C. (1995). Teaching chemical equilibrium and thermodynamics in undergraduate general chemistry classes. Journal of Chemical Education, 72(10), 879–881.

Ben-Zvi, R., Silberstein, J., & Mamlok, R. (1989). Macro-micro relationships: A key to the world of chemistry. In: P. Licht & A. J. Waarlo (Eds.), Relating macroscopic phenomena to microscopic particles. A central problem in secondary science education (pp. 184–197). Utrecht: CDss Press.

Coll, R. K., & Treagust, D. F. (2003). Investigation of secondary school, undergraduate, and graduate learners' mental models of ionic bonding. Journal of Research in Science Teaching, 40(5), 464–486.

Copolo, C. E., & Hounshell, P. B. (1995). Using three-dimensional models to teach molecular structures in high school chemistry. Journal of Science Education and Technology, 4(4), 295–305.

diSessa, A. A., Hammer, D., Sherin, B. L., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. Journal of Mathematical Behavior, 10, 117–160.

diSessa, A. A., & Sherin, B. L. (2000). Meta-representation: An introduction. Journal of Mathematical Behavior, 19(4), 385–398.

Elby, A. (2000). What students' learning of representations tells us abot constructivism. Journal of Mathematical Behavior, 19, 481–502.

Erduran, S. (2005). Applying the philosophical concept of reduction to the chemistry of water. Science & Education, 14(2), 161–171.

Eylon, B., Ben-Zvi, R., & Silberstein, J. (1986). Is an atom of copper malleable? Journal of Chemical Education, 63(1), 64–66.

Fry, B., & Raes, C. (2001). Processing (Version 2.0) [Computer software]. Cambridge, MA: MIT.

Geier, R., Blumenfeld, P., Marx, R.W., Krajcik, J. S., Fishman, B., Soloway, E., et al. (2008). Standardized test outcomes for students engaged in inquiry-based science curriculum in the context of urban reform. Journal of Research in Science Teaching, 45(8), 922–939.

Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. Science Education, 80(5), 509–534.

Hickey, D. T., Kindfield, A. C. H., Horwitz, P., & Christie, M. A. (1999). Advancing educational theory by enhancing practice in a technology-supported genetics learning environment. Journal of Education, 181(2), 25–55.

Johnstone, A. H. (1982). Macro- and micro-chemistry. School Science Review, 64, 377–379.

Johnstone, A. H. (1993). The development of chemistry teaching. Journal of Chemical Education, 70(9), 701–705.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: an analysis of the failure of constructivist, discover, problem-based, experiential, and inquiry-based teaching. Educational Psychologist, 41(2), 75–86.

Kohl, P. B., & Finkelstein, N. D. (2006). Effects of representation on students solving physics problems: A fine-grained characterization. Physical Review Special Topics-Physics Education Research, 2(1), 010106.

Kozma, R., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. Journal of Research in Science Teaching, 34(9), 949–968.

Kozma, R., Russell, J., Jones, T., Marx, N., & Davis, J. (1996). The use of multiple, linked representations to facilitate science understanding. In: S. Vosniadou R. Glaser, E. De Corte, & H. Mandl (Eds.), International perspectives on the psychological foundations of technology-based learning environments (pp. 41–60). Hillsdale, NJ: Erlbaum.

Lee, O., Eichinger, D. C., Anderson, C. W., Berkheimer, G. D., & Blakeslee, T. S. (1993). Changing middle school students' conceptions of matter and molecules. Journal of Research in Science Teaching, 30(3), 249–170.

Levy, S. T., & Wilensky, U. (2009a). Crossing levels and representations: The Connected Chemistry (CC1) curriculum. Journal of Science Education and Technology, 18(3), 224–242.

Levy, S. T., & Wilensky, U. (2009b). Students' learning with the Connected Chemistry (CC1) curriculum: Navigating the complexities of the particulate world. Journal of Science Education and Technology, 18(3), 243–254.

Linn, M. C., Lee, H.- S., Tinker, R., Husic, F., & Chiu, J. L. (2006). Teaching and assessing knowledge integration in science. Science, 313, 1049–1050.

Mathewson, J. H. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. Science Education, 83, 33–54.

Rappoport, L. T., & Ashkenazi, G. (2008). Connecting levels of representation: Emergent versus submergent perspective. International Journal of Science Education, 30(12), 1585–1603.

Russell, J., Kozma, R., Jones, T., Wykof, J., Marx, N., & Davis, J. (1997). Use of simultaneous-synchronized macroscopic, microscopic, and symbolic representations to enhance the teaching and learning of chemical concepts. Journal of Chemical Education, 74(3), 330–334.

Stieff, M. (2005). Connected Chemistry—A novel modeling environment for the chemistry classroom. Journal of Chemical Education, 82(3), 489–493.

Stieff, M., & McCombs, M. (2006). Increasing representational fluency with visualization tools. In: S. Barab, K. E. Hay, & D. T. Hickey (Eds.), Proceedings of the Seventh International Conference of the Learning Sciences (ICLS) (vol. 1, pp. 730–736). Mahwah, NJ: Erlbaum.

Stieff, M., & Wilensky, U. (2003). Connected Chemistry - Incorporating interactive simulations into the chemistry classroom. Journal of Science Education and Technology, 12(3), 285–302.

Wilensky, U. (1999). NetLogo (Version 3.0) [Computer Program]. Evanston, IL: Center for Connected Learning and Computer Based Modeling, Northwestern University.

Wilensky, U. (2001). Modeling nature's emergent patterns with multi-agent languages. Paper presented at the EuroLogo 2001, Linz, Austria.

Wu, H. -K., Krajcik, J. S., & Soloway, E. (2001). Promoting conceptual understanding of chemical representations: Students' use of a visualization tool in the classroom. Journal of Research in Science Teaching, 38(7), 821–842.

Yezierski, E. J., & Birk, J. P. (2006). Misconceptions about the particulate nature of matter: Using animations to close the gender gap. Journal of Chemical Education, 83(6), 9401–9403.

Yip, J. C., Jaber, L. Z., & Stieff, M. (2011). Examining changes in students' coordination of verbal and pictorial chemical representations in response to instruction. Paper presented at the American Educational Research Association.