Visualization and interactivity in the teaching of chemistry to science and non-science students

Bhawani Venkataraman

Received 16th September 2008, Accepted 26th November 2008
DOI: 10.1039/b901462b

A series of interactive, instructional units have been developed that integrate computational molecular modelling and visualization to teach fundamental chemistry concepts and the relationship between the molecular and macro-scales. The units span the scale from atoms, small molecules to macromolecular systems, and introduce many of the concepts discussed in a first year undergraduate class, such as atomic structure, chemical bonding, the molecular nature of physical properties and structure-function relations in macromolecular systems. The units were used in an introductory level chemistry course for non-science majors and students interested in non-traditional science careers. Assessment of these units indicated that the students are successfully learning fundamental concepts, value the computer-based learning aids, and begin to develop mental models of the molecular scale.

Keywords: visualization, molecular modelling, non-science majors, assessment, mental models

Introduction

An essential requirement for learning chemistry is the ability to form mental models of processes at the molecular scale (Gilbert, 2005; Russell and Kozma, 2005; Chittleborough and Treagust, 2007). Yet, students find this to be one of the most challenging aspects of chemistry courses (Gabel *et al.*, 1987; Nakhleh, 1992; Gabel, 1993). Lacking a clear mental model of the molecular scale, students often cannot appreciate the relationship between the molecular scale and observed macroscopic phenomena, and ultimately, they have difficulty seeing the relevance of chemistry in their lives or the role of chemistry in addressing issues facing society.

An approach that is increasingly being used to help students develop mental models is computer visualizations of molecular systems and processes (Wu and Shah, 2004; Gilbert, 2005; Jones *et al*. 2005; Rapp, 2005; Tasker and Dalton, 2006). As stated in a 2001 NSF workshop 'Molecular Visualization in Science Education', *"Because basic 3D spatial relationships in molecules have systematic and profound causal significance, chemistry is an extraordinarily fertile field for visual learning"*(Jones *et al*., 2001, p. 6).

Research on computer-based visualizations and animations indicates that these tools can be helpful in the development of mental models and images of molecular level processes (Gilbert, 2005; Rapp, 2005; Russell and Kozma, 2005). Studies reveal that 3D visualizations and animations enhance students' conceptual understanding and spatial abilities (Wu and Shah, 2004; Williamson and Jose, 2008). At the same time they have to be used carefully, as misconceptions can also be established. As pointed out by Tasker and Dalton *"to use animations effectively, we need to direct our students' attention to their key features, avoid overloading working memory, and promote meaningful integration with prior knowledge"* (Tasker and Dalton, 2006, p. 156).

This paper presents a set of instructional units that integrate a commercial molecular modelling software package, Spartan Student Edition (www.wavefun.com). As described below, the units emphasize basic chemical concepts, and guide students using the software to build, visualize, interact, and simulate molecular-level systems and processes. The units help students develop a visual understanding that spans the scale from individual atoms to complex macromolecular systems, and highlights the relationship between molecular-scale processes and macro-scale outcomes.

While there have been previous studies that use commercial modelling packages to teach undergraduate chemistry to science and engineering majors (Shusterman and Shusterman, 1997; Ealy, 1999; Sanger and Badger, 2001; Erny *et al*., 2006; Tuvi-Arad and Gorsky, 2007), this work focuses on students who are not pursuing traditional chemistry careers or are non-science majors. The units are used in an introductory chemistry course that is part of an interdisciplinary science program. Most of the students entering the course do not perceive themselves as 'strong in science'.

This study looks at how the visualization-based units help non-science majors and students interested in non-traditional science careers learn fundamental chemical concepts. It also looks at students' perceptions on the role of visualizations in helping them learn concepts and the development of mental images and models of molecular scale processes.

Method

Setting

The instructional units developed for this study have been incorporated in a course that is taught in the Interdisciplinary Science program of Eugene Lang College, a division of The

Department of Natural Sciences and Mathematics, Eugene Lang College, The New School for Liberal Arts, New York, NY 10011, USA.
E-mail: venkatab@newschool.edu

Table 1 Topics, learning outcomes and visualization activities in each unit

Topic covered and learning outcomes	Visualization activities
Unit 1: Why do atoms bond? Formation of covalent bond, attractive and repulsive forces, role of energy in bond formation and dissociation, bond length, bond energy	View movies and plots that depict the change in potential energy as a function of inter-nuclear distance (see Fig. 1)
Unit 2: How do atoms bond? Electron configuration, valence electrons, molecular structure and shape, influence of the nature of the atoms in a molecule on molecular shape, factors that influence bond length and bond angles	Build molecules and investigate the relation between molecular structure and shape. Visualize the influence of non-bonding electrons on molecular shape (see Figure 2)
Unit 3: What are the consequences of chemical bonding? Electronegativity, polarity, influence of molecular shape on polarity, dipole moments, dipole-dipole and dispersion interactions	Construct electrostatic potential maps as models for electron distribution in a molecule (Shusterman and Shusterman, 1997; Ealy, 1999; Sanger and Badger, 2001). Investigate the effect of molecular geometry on polarity
Unit 4: What are the consequences of intermolecular interactions? Role of energy in influencing inter-molecular interactions	View movies and plots that display the change in potential energy as a function of distance between two molecules
Unit 5: What determines the unique properties of water? Hydrogen bonding, influence of inter-molecular interactions on physical properties	Create small clusters to investigate the effect of molecular geometry and polarity on hydrogen bonding between molecules
Unit 6: What factors influence solubility? Solubility of covalent compounds, hydrophobic, hydrophilic, amphiphilic interactions, solubility of ionic compounds.	Model interactions that determine solubility by building clusters that compare the interactions between oil, water and soap
Unit 7: What factors influence protein structure and function? Role of non-covalent interactions in influencing protein structure and function, self-assembly.	Visualize the effect of hydrogen bonding on shape of peptides. Chime activities on protein structure and function
Unit 8: What factors influence nucleic acid structure and function? Role of non-covalent interactions in influencing function, self-assembly.	Visualize the effect of hydrogen bonding on base pairing. Chime activities on nucleic acid structure and function

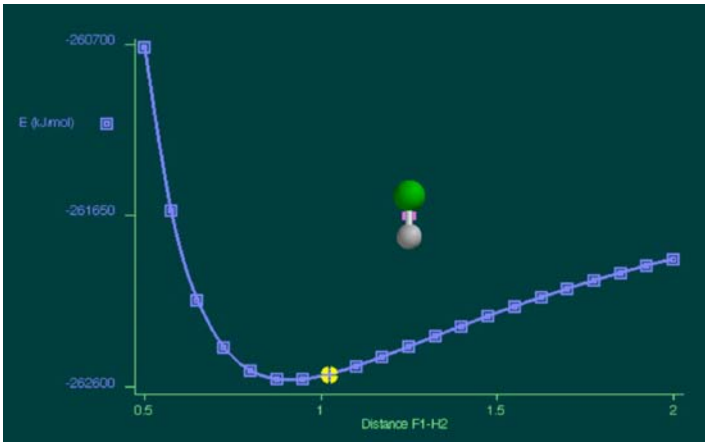

Fig. 1 Screen shot from a video showing the change in potential energy as a function of the distance between an H and F atom.

New School. The course ‘Chemistry of Life’ uses chemical evolution as a thematic focus (Venkataraman, 2008). The instructional units cover approximately 55% of the course content.

Pre-course surveys show that more than 90% of the students have taken chemistry in high school, but only one student out of twenty-three took Advance Placement Chemistry. The students are a mix of Interdisciplinary Science (IS) majors and non-science students (*e.g.*, writing, theatre and art). The course is required for IS majors who are interested in non-traditional science careers in fields such as environmental and health policy, science education, and science writing. The non-science students take the course as an elective.

Overview of instructional units

Eight units have been developed each of which incorporate molecular modelling, visualization, and simulation activities. The eight units span the scale from atoms, small molecules, and larger molecules to macromolecular systems. The logic behind the sequence is to introduce many of the concepts discussed in a first year undergraduate class, such as atomic structure, chemical bonding, the molecular nature of physical properties, and structure-function relations between small molecular and large macromolecular systems. As the units move from individual atoms to large complex systems, students relate their understanding to macro-scale outcomes and observables through predictions, questions, and simulations.

Table 1 summarizes the eight units listing the topics covered and learning outcomes of each unit, along with brief descriptions of the visualization activities in each.[1] Each instructional unit has a well-defined structure, which consists of:

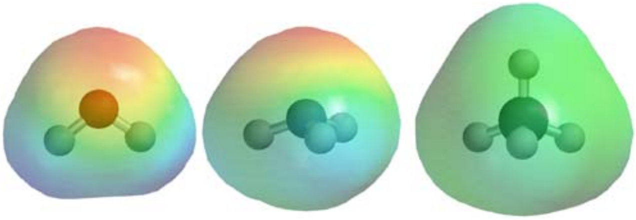

Fig. 2 Electrostatic potential maps of H_2O, NH_3 and CH_4. These maps are used to discuss the consequence of electronegativity on electron distribution and the influence of molecular shape on molecular polarity.

- A class discussion in which the basic concepts covered by the unit are introduced;
- Time devoted to performing the visualization activity on laptop computers, guided by specific questions that need to be answered;
- Homework in which summative questions are answered.

The visualization activities are done in groups of 2-3 students working together on laptops provided to them. All the groups do the same activities at the same time. A unit typically spans two class periods. Students use Spartan Student Edition to build molecular structures and systems, and to explore concepts and the implications of those concepts at the molecular and macro-scale. Through the repeated use of the software to model simple and complex systems, the students learn how they can make use of the models to better understand the fundamental concepts discussed in class. In units 7 and 8, in addition to using Spartan, the activities include Chime exercises (http://www.mdl.com/products/framework/chime/) on protein and nucleic acid structure and function that have been developed by others.

Assessment tools

Five assessment tools were used in this study. Each tool is described below. These tools are used to assess:

1. The effectiveness of the units in supporting student learning of concepts
2. Student perceptions of the 3D visualization and interactivity in helping them to learn
3. The effectiveness of the units in helping students to develop mental models

Tool 1 - Pre- and post-course questions

On the first day of class, students fill out a questionnaire that gathers background information (*e.g.* prior chemistry and science courses) and their baseline understanding of chemistry and concepts that will be discussed in class. At the end of the course they fill out a questionnaire that asks the same questions (except for their background information). The pre- and post- course answers are compared to assess the maturation of responses and whether key concepts were understood. Three of the questions relate specifically to material covered in the instructional units and were used in the assessment. They are:

Question 1: How would you describe a water molecule?

Question 2: Liquid water is considered to be a necessary ingredient for life. From a chemical perspective what determines water's role in life?

Question 3: What is self-assembly and why is it relevant to life?

The responses to these questions were scored using the rubric adapted from Jennings *et al.* (2007) given in Table 2.

Table 2 Scoring rubric used for student responses to pre and post course questions. The rubric is adapted from Jennings *et al.* (2007)

Score	Criteria for score
0	Blank or *"I don't know"*
1	Irrelevant or unclear response
2	Responses that include unrelated or incorrect information
3	Responses that show partial understanding of concept, but include statements that demonstrate a misconception
4	Responses show understanding of concept (at least one significant component), but not clearly explained or incomplete explanation
5	Responses that indicate a strong understanding and include more than one relevant concept

Table 3 Examples of conceptual questions asked on tests

Direct Question	Explain why bond breaking is an endothermic (energy absorbing) process, but bond making (formation) is an exothermic process?
Extension Question	If 'life' (perhaps as we don't know it) could develop on Titan in liquid methane, what kind of interactions would this kind of life depend on? Explain. How successful do you think life dependent on these kinds of interactions would be? Explain.

Tool 2 - Assigned questions

Questions were assigned as homework and given grades for units 2, 3, 4, 5, and 6 in the 2007 class. These grades were used in the assessment. For the other units in 2007, and all the units in 2006, the questions were discussed in class while the unit was being done and therefore were not graded. In both years, students were still required to submit written responses to questions in all units even if a grade was not assigned.

Tool 3 - Conceptual questions on final exam

Some of these questions test understanding of basic concepts discussed in class ('Direct' questions). Others ('Extension' questions) require the students to look at problems they have not seen before or to analyse a problem related to chemical evolution, the overall theme of the course. Table 3 gives an example of each type of question.[2]

Tool 4 - Reflective summaries

Three times over the course of the semester, students were asked to hand in a written reflective summary. The questions in Table 4 were provided to guide the students in writing their summaries.

Tool 5 - End of semester questions:

At the end of the semester, a course evaluation survey gauged the students' reactions to different aspects of the course. Two questions on this survey emphasize the role of the

Table 4 Guiding questions for reflective summaries

(i) What concepts and ideas have been discussed so far
(ii) What have you learned so far?
(iii) How did you learn it?
(iv) What remains unclear?
(v) How do you relate what you have learned so far to the role of chemistry in the origins of life?
(vi) If you were the professor, what questions would you ask your students to find out if they understood the material?
(vii) Anything else you would like to add to your summary.

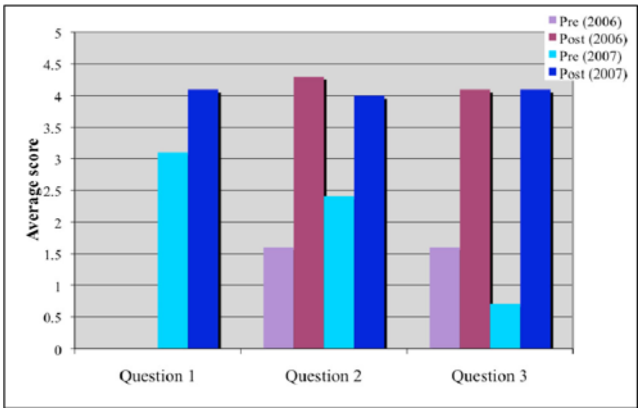

Fig. 3 Average scores of pre- and post- course questions. The questions are listed in the Assessment tools section. Question 1 was not asked in 2006.

visualization activities. The two questions are:

1. Which activities helped most in understanding a chemical concept and why?
2. Do you think Spartan helped you learn the chemical concepts discussed? If yes, please explain how (and give examples if possible). Do you think you would have learned as well without Spartan?

Assessment results

The data discussed here have been compiled from the two most recent classes; a class in 2006 with fourteen students and a class in 2007 with nine students.

Tool 1 - Pre- and post-course questions

Figure 3 compares average scores for pre- and post- responses to the three questions that draw on concepts discussed in the units. Tables 5 and 6 show examples that illustrate how the scores were assigned.

Tool 2 - Assigned questions

The average score for the five graded assignments in 2007 are shown in Table 7. Answers to the activities in units 5 and 6 were submitted as one assignment. The overall average score for all the graded assignments was 84%.

Tool 3 - Conceptual questions on final exam

Table 8 lists the average student scores on the conceptual questions asked on the final exam for both the direct and extension questions.

Table 5 Representative student responses to the question 'Liquid water is considered to be a necessary ingredient for life. From a chemical perspective what determines water's role in life?' and assigned scores using the rubric in Table 2. Also indicated is whether the comments are pre- or post- course

Representative responses	Score
95% of the human body is made up of water. It's a necessity for life on earth. *(Pre)*	2
As a solvent, a substrate, environment, water being such a versatile and unique molecule it allows for reactions, organization, and even as an ecosystem. *(Post)*	3
Hydrogen bonding, polarity, dipole moments and its soluble characteristics (insoluble with oil) *(Post)*	4
Water is a very unique molecule. Its extensive hydrogen bonding ability causes it to form strong networks of interactions that make its boiling point very high, as well as high surface tension. Water's polarity allows it to interact in important ways with many different molecules and makes it an excellent solvent. Water is required by many of the chemical reactions that life depends on. Living things are made up mostly of water *(Post)*	5

Table 6 Representative student responses to the question 'What is self-assembly and why is it relevant to life?' and assigned scores using the rubric in Table 2. Also indicated are whether the comments are pre or post course

Representative responses	Score
The ability of elements to interact under practical conditions? Requires very little human effort or energy? *(Pre)*	2
Self-assembly is one of the most necessary concepts. I think it allows for an inherent organization/structures and allows for complex system to form on their own. Without it, I'm not sure if life would exist. *(Post)*	3
Self-assembly is the tendency of atoms to assemble in a certain formation that minimizes its energy. This creates what we know as 'order' in the world. *(Post)*	4
The way atoms and molecules orient themselves based on polarity, attraction, bonding. Some of the most fundamental structure in life resulted from this - e.g. DNA helix. *(Post)*	5

Table 7 Average student scores of assignments in units 2, 3, 4, 5 and 6

	Unit 2	Unit 3	Unit 4	Units 5 and 6
% Average Score	81	91	85	77

Table 8 Average scores on conceptual questions

	Average Score (%) 2006 (N=14)	Average Score (%) 2007 (N=9)
Direct	74	79
Extension	66	74
.		

Tool 4 - Reflective summaries

In the reflective summaries, all the students commented on the importance of the activities in helping them understand and visualize concepts. Table 9 contains representative comments from different students' reflective summaries. Table 10 lists representative answers in response to the question 'If you

Table 9 Representative comments from students' reflective summaries

1. *"The covalent bonding activity, which included the movies of different chemical bonds, as well as graphs showing energy as a function of distance between atoms, was extremely helpful for me because it gave me a picture in my mind of the interaction between atoms"*
2. *"We [then] viewed the molecule in different models. Wire, ball and wire, tube, ball and spoke, and space filling. All allowed us to better view the structure of the molecule. But the space-filling model was my favourite. It was because it showed the electron clouds of each molecule. It gave a better visual understanding of how the electrons are inter-shared between the different atoms."*
3. *"In terms of basic chemistry, I have also gained a good understanding of polarity, particularly through Spartan simulations in class. Since I am a visual learner, the Spartan activity in which we modelled molecules and saw their polarity in color-coding was very helpful. I can now visualize a molecule and understand if it is polar or not. Polar molecules interact in dipole-dipole interactions."*
4. *"Learning about self-assembly, especially through the lab we did in class with water, oil, and soap, helped me understand my project topic better. I still have images of this lab in my head that I think of every time I wash dishes, or am cooking with oil. I explained self-assembly using the example of amphiphilic soap molecules forming micelles in water, and how that is used to remove the grease on dirty dishes to my family last night, and they were fascinated, and astonished by how well I could explain it."*
5. *"In class we have been discussing these concepts and then applying them to Spartan activities, which have been very helpful in visualizing the concepts at hand. In between we have been analyzing the outcomes and determining what each result means in specific and more general ideas. This analysis's are really useful because it allows us to stop and think about what we have learned so far and what the activities have taught us. For me, the visual activities have been very useful in grasping the information."*
6. *"As the semester moved forward and we became more interactive with our learning and I was really able to visualize the molecules reacting and bonding. With the help of Spartan we were able to piece together information finally making sense of it as a whole. I had a light bulb moment when after using hydrogen bonds in the Spartan program a little after class when I was working on my paper it finally clicked. When I was watching those molecules hydrogen bond they were actually self-assembling."*
7. *"For example, the question on the final exam about why enzymatic activity shuts down when body temperature becomes very high required me to apply all of my knowledge of proteins, in addition to my understanding of how temperature affects hydrogen bonding, which I learned about through studying water's unique properties. I knew that enzymes interact with substrates like a lock and key, and that the very specific shapes the enzymes require are due to hydrogen bonding. I also knew that high temperatures break the hydrogen bonds of water, causing it to boil. Therefore, I was able to understand that high temperatures would break the hydrogen bonds of the enzymes, causing them to lose their shape and be unable to interact with the substrates. Again, the Spartan activities, and also the website we looked at with models of different protein structures, helped me to understand proteins, since I am a visual learner".*
8. *"The class and the SPARTAN modelling system, has indeed, illuminated my knowledge of life's complexity and its roots in DNA. Deoxyribonucleic acid is a library of information tightly coiled into a double helix."*

were the professor, what questions would you ask your students to find out if they understood the material?'

Tool 5 - End of semester questions

At the end of the semester, a course evaluation survey gauged the students' reactions to different aspects of the course. Two questions on this survey emphasize the role of the visualization activities. Table 11 shows these questions and representative answers. The student responses to Question 1 show that 86% (12/14 students) in 2006 and 100% (9/9 students) in 2007 found the Spartan activities to be the course component that was the most helpful in communicating concepts. The responses to Question 2 show that in both 2006 and 2007, the majority of the students answered 'yes' when asked whether Spartan helped them learn the chemistry concepts taught in the course.

Table 10 Representative answers in response to "If you were the professor, what questions would you ask your students to find out if they understood the material?"

1. *Why do atoms bond? What type of bond do they have and how does it influence the behavior of the molecule?"*
2. *"How does intermolecular interaction relate to the assembly of macromolecules? Why is water the universal solvent?"*
3. *"Why is polarity important? Why is water the essential ingredient for life? Why doesn't water mix with oil? Why is the water molecule bent? What is a dipole-dipole interaction, and give an example of one in real life?"*
4. *"Why can't similar or the same nucleotide bases bond together in the DNA helix? What are the main differences between a beta sheet and an alpha helix in terms of structure and function?"*

Table 11 Representative students' comments on the end of semester survey

Question 1: "Which activities helped most in understanding a chemical concept and why?"

"The Spartan activities were always helpful, especially for me, because I am a visual learner, especially the concept of polarity"

"Spartan activities, because it imitated chemical reactions we could not do in labs."

"Spartan - it is a good visual tool, interactive and makes the student learn by his or herself how molecules are assembled and how they interact"

"Spartan - because you have a chance to use a visual aid in understanding the chemistry."

Question 2: "Do you think Spartan helped you learn the chemical concepts discussed? If yes, please explain how (and give examples if possible). Do you think you would have learned as well without Spartan?"

"Yes, yes, yes! Also, the fact that the 'visual models' were included in the class description was a major factor in my decision to take the class because I felt it would be a unique opportunity for me to apply my skills to learn chemistry".

"Yes because it displayed the actual behavior instead of just thinking about it in our heads"

"Yes it helped me visualize the concepts, which is very helpful to my learning. It also helped me put all the concepts together"

"I thought Spartan was a great tool for understanding concepts such as bond energy and polarity my understanding was greatly improved by Spartan."

"Yes, visually Spartan was an excellent way to see microscopic structures and mechanisms at work."

"*Spartan was helpful sometimes, but often times the models confused me*"

"… it might have been a bit overused. It can be tedious."

"I see Spartan as an important tool in the class. But some concepts could have been explained without it"

Discussion

The assessment data support the following conclusions:

- **Student learning of concepts:** The fundamental concepts embedded in the activities were effectively communicated to the students.
- **Student perceptions of the visualization activities**: All the students felt that their success in understanding the concepts is largely due to the visualization activities.
- **Development of mental models**: The students used language that suggests that they have gone beyond abstract integration of the concepts discussed in class and have succeeded in 'visualizing' the material.

The discussion below elaborates on how the data support these conclusions.

Student learning of concepts

Student learning of fundamental concepts was assessed through four of the five tools: assigned questions, conceptual questions on the final exam, pre and post- course questions and reflective summaries. The average scores for the assigned questions in the five units that were graded in 2007 and the direct and extension questions on the final exam indicate that majority of students understood the concepts. However, recognizing that these average scores are based on small sample sizes, other indicators have also been used to demonstrate the effectiveness of the instructional units on student learning. For example, it was observed that over the course of the semester, as students' understanding developed, answers to questions became more detailed and demonstrated increasing comfort with terms and concepts. Analyses of answers to exam questions indicate that points deducted were typically due to incomplete answers rather than wrong answers. The majority of students who did not receive full credit for a question received partial credit.

The data in Figure 3 compare the pre and post-course responses to questions that assess understanding of concepts. The data show a marked increase (>25%) between the pre- and post- scores. In 2006, 12 out of 14 students scored higher in the post response to Question 2 and 14/14 students scored higher in the post response to Question 3. In 2007 8/9 students scored higher in the post response to Questions 1 and 3 and 9/9 students scored higher in the post response to Question 2. Comparisons of the pre- and post-course questions reveal the post- course responses to be more sophisticated and detailed, with a deeper understanding of the chemical relevance of the question and the significance of 3D shapes and interactions. For example, the pre-course answers to the two questions on water show that students come into the course with a vague understanding of water and its importance to life. The post-course responses demonstrate an understanding of how the water structure contributes to its unique properties and its role in the existence of life on Earth. In answering this question, students draw from understanding developed in units 2, 3, 4, 5, and 6. The post-responses to the question on self-assembly reveal an integration of concepts.

The reflective summaries are rich and descriptive and demonstrate retention of information over the duration of the course. The students' ability to explain what they have learned demonstrates an understanding of the material and confidence in their abilities. Comments 4, 6, 7 and 8 in Table 9 and the student questions in Table 10 are indicative of students' understanding of concepts and comfort with terms, concepts, applications and integration of knowledge.

Student perceptions of the visualization activities

Students' responses to the questions asked at the end of the semester, reveal the importance the visualization activities in helping them understand concepts. Comments such as *"… it displayed the actual behaviour instead of just thinking about it in our heads"* or *"Visually Spartan was an excellent way to see microscopic structures and mechanisms at work"* suggest that students value highly learning through a visual tool to understand and 'relate' to the molecular scale. In both years, the students overwhelmingly supported the importance of the visualization activities in helping them learn the course material.

Over the two years, three students expressed some reservations about the visualization activities. While all three acknowledged that the activities helped them learn, one felt that the models were confusing and two felt they were over used.

Concurrence of positive students' attitudes and perceptions of the visualization activities comes from the reflective summaries. In 2007, in all the students' reflective summaries it was clear that they were learning concepts from the visualization activities, and that they felt that the activities were important in helping them understand the concepts. The representative comments from these summaries in Table 9 are evidence of this positive impact. Comments such as *"I had a light bulb moment when after using hydrogen bonds in the Spartan program a little after class when I was working on my paper it finally clicked. When I was watching those molecules hydrogen bond they were actually self-assembling"* or *"I explained self-assembly using the example of amphiphilic soap molecules forming micelles in water, and how that is used to remove the grease on dirty dishes to my family last night, and they were fascinated and astonished by how well I could explain it"* reveal the power of visualizations in helping students develop mental models of molecular level processes.

Anecdotal evidence of class observations on the mood in the class further supports the positive effect of the activities. When students are performing the visualization activities, they are engaged and work collaboratively in performing the activities. Students are actively involved in the process of building and interacting. They work together explaining observations and ideas to each other. Students often comment in class that they are 'visual learners', that the activities are 'helping them understand', and that they feel they could not have learned the basic chemistry concepts as well without the visualization activities.

Development of mental models

The data from all five assessment tools support the conclusion that the visualization activities are helping students develop mental models of concepts and chemical processes at the molecular scale. Comparison of the pre- and post- responses, reflective summaries, and end of semester surveys shows an increased use of language that reflects reliance on mental imagery. Comments in the reflective summaries and the end of semester survey (*"… it displayed the actual behavior instead of just thinking about it in our heads"* or *"visually Spartan was an excellent way to see microscopic structures and mechanisms at work"*) are typical of language used more and more frequently as the semester progressed. The students' ability to answer the conceptual questions at the end of each unit and on the final exam indicates that they are drawing from their mental images of relevant concepts and processes.

Future work

Analysis of test scores reveals that students struggle to understand dispersion interactions. Students are also challenged to understand the influence of atomic size on hydrogen bonding. Further study is therefore needed to find ways to use the visualization and modelling capabilities to help students understand these concepts.

The next phase of this work will be to gather more direct evidence of the mental images students develop as a result of their use of the visualization activities. The data collected thus far relies on verbal comments made by the students and on test scores. A possibility being considered for the future is to ask students to draw images or create animations of molecular systems and processes by using a molecular animation program called ChemSense (http://chemsense.org/).

Challenges

For some students, the activities and Spartan have to be used carefully. One student commented that the models were confusing (*"Spartan was helpful sometimes, but often times the models confused me."*). Two students felt less use of Spartan may have been better (*"… it might have been a bit overused. It can be tedious." "I see Spartan as an important tool in the class. But some concepts could have been explained without it."*) While the majority of students in this class agreed that the visualizations helped them, these comments suggest that different learning styles need to be accounted for in future classes.

Adaptability

This study was conducted in relatively small classes of nine and fourteen students. This made it possible to integrate the visualization activities into the classroom. Courses with larger enrollments could integrate visualizations into recitations or discussion sessions. While the units as described here are designed for non-chemistry majors, the underlying concepts in these units are integral to any general chemistry course and could be adapted for courses for chemistry majors.

Conclusions

The activities developed and assessed in this study have been used to teach fundamental chemistry concepts to students who are not traditional science majors and to non-science majors. The study supports the following conclusions:

- The instructional units are effective in helping students learn the underlying chemical concepts and in understanding the role of the molecular scale on observed phenomena.
- Students appreciate and value the use of 3D visualizations and interactivity in learning the course material.
- Students are using the visual activities to develop mental models of molecular level systems and processes.

The effectiveness of the units in conveying the influence of the molecular scale on observed phenomena suggests that visualizations and simulations can play an important role in engaging the larger community of undergraduate non-science majors to learn chemistry. The conclusions from this study can also be extended to the teaching of chemistry to science majors, supporting the recommendations put forward by the 2001 NSF Workshop.

Acknowledgment

The author gratefully acknowledges support for this project from the National Science Foundation through a CCLI-A&I grant (DUE-0510543). Any opinions, findings, and conclusions expressed in this paper are those of the author and do not necessarily reflect the views of the NSF. Support for this work was also provided by Eugene Lang College, The New School for Liberal Arts.

Notes and References

[1] A complete description of the instructional units can be obtained by contacting the author.

[2] A compilation of the questions used in this study can be obtained by contacting the author.

Chittleborough G. and Treagust D. F., (2007), The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level, *Chem. Educ. Res. Pract.*, **8**, 274-292.

Ealy J. B., (1999), A student evaluation of molecular modelling in first year college chemistry, *J. Sci. Educ. Tech.*, **8**, 309-321.

Erny C., Bouvier D., Bloch G., Laemmel C. and Leseney A-M., (2006), Assessing the educational effectiveness of a CAL tutorial. Structure and molecular dynamics in biology; Part 1: water and molecular interactions, *Chem. Educ. Res. Pract.*, **7**, 248-275.

Gabel D. L., Samuel K. V. and Hunn D., (1987), Understanding the particulate nature of matter, *J. Chem. Educ.*, **64**, 695-697.

Gabel D. L., (1993), Use of the particle nature of matter in developing conceptual understanding, *J. Chem. Educ.*, **70**, 193-194.

Galley W. C., (2004), Exothermic bond breaking: a persistent misconception, *J. Chem. Educ.*, **81**, 523-525.

Gilbert J. K., (2005), Visualization: a metacognitive skill in science and science education, *Visualization in science education*, J. K. Gilbert, (Ed.), Springer, pp. 9-27.

Jennings K. T., Epp E. M. and Weaver G. C., (2007), Use of a multimedia DVD for physical chemistry: analysis of its effectiveness for teaching content and applications to current research and its impact on student views of physical chemistry, *Chem. Educ. Res. Pract.*, **8**, 308-326.

Jones L., Jordan K. and Stillings N., (2001), Report from the molecular visualization in science education workshop. http://pro3.chem.pitt.edu/workshop/workshop_report_180701.pdf.

Jones L. L., Jordan K. D., Stillings N. A., (2005), Molecular visualization in chemistry education: the role of multidisciplinary collaboration, *Chem. Educ. Res. Pract.*, **6** 136-149.

Nakhleh M. B., (1992), Why some students don't learn chemistry, *J. Chem. Educ.*, **69**, 191-196.

Rapp D., (2005), Mental models: theoretical issues for visualizations in science education, J. K. Gilbert, (Ed.), *Visualization in science education*, Springer, pp. 43-60.

Russell J. and Kozma R. B., (2005), Assessing learning from the use of multimedia chemical visualization software, J. K. Gilbert (Ed.), *Visualization in science education*. Springer, pp. 299-322.

Sanger M. J. and Badger II S. M., (2001), Using computer-based visualization strategies to improve students' understanding of molecular polarity and miscibility, *J. Chem. Educ.,* **78**, 1412-1416.

Shusterman G. P. and Shusterman A. J., (1997), Teaching chemistry with electron density models, *J. Chem. Educ.,* **74**, 771-776.

Tasker R. and Dalton R., (2006), Research into practice: visualisation of the molecular world using animations, *Chem. Educ. Res. Pract.,* **7**, 141-159.

Tuvi-Arad I. and Gorsky P., (2007), New visualization tools for learning molecular symmetry: a preliminary evaluation, *Chem. Educ. Res. Pract.,* **8**, 61-72.

Venkataraman B., (2008), Chemistry of life: chemical evolution as a theme for teaching undergraduate chemistry, in *Chemical evolution across space and time: from the big bang to prebiotic chemistry*, L. Zaikowski and J. Friedrich (Eds.), American Chemical Society Symposium Series, pp**.** 378-388.

Williamson V. M. and Jose T. J., (2008), The effects of a two-year molecular visualization experience on teachers' attitudes, content knowledge, and spatial ability, *J. Chem. Educ.,* **85**, 718-723.

Wu H.-K. and Shah P., (2004), Exploring visuospatial thinking in chemistry language, *Sci. Educ.,* **88**, 465-492.