ChemVLab+: Evaluating a Virtual Lab Tutor for High School Chemistry

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Abstract: Conceptual understanding in chemistry requires students to connect quantitative calculations, microscopic chemical processes (e.g., atoms and molecules), and macroscopic outcomes (e.g., concentrations, color, temperature). The ChemCollective Virtual Lab's interactive simulation environment fosters the mapping between these representations by providing students with a fully functional online chemistry lab with realistic chemicals, glassware, and equipment. In the ChemVLab+ project (www.chemvlab.org), we enhance the virtual lab by developing intelligent tutoring for this open-ended simulation environment and creating embedded formative assessment activities. Students have opportunities to apply chemistry knowledge to meaningful contexts and receive immediate, individualized feedback as the system estimates their proficiency based on their actions. We report findings from a classroom field study of ChemVlab+ activities. Data from classroom observations, pre-posttest learning gains, detailed log file analyses, and teacher interviews suggest that students were actively engaged, that students improved their understanding of chemistry, and that teachers found the activities worthwhile.

Introduction

Typical high school chemistry instruction consists of quantitative problem solving activities with the implicit assumption that students are learning core concepts in chemistry through the manipulation of numbers and symbols. Successful performance on complex calculations is taken as evidence of student mastery. However, research in chemistry education questions whether quantitative ability reflects conceptual understanding. Students have great difficulty connecting the mathematical representations with the underlying chemistry concepts and even high achieving students may lack basic knowledge of core principles (e.g., Bodner & Herron, 2002; Gabel & Bunce, 1994; Nakhleh & Mitchell, 1993; Smith & Metz, 1996). For instance, Smith & Metz (1996) found that students who performed well on traditional assessments in acid/base chemistry failed to identify strong versus weak acids when shown diagrams, suggesting that definitions and terms were used without true comprehension. Similarly, Nakhleh & Mitchell (1993) found that students given both conceptual and algorithmic items paired for identical concepts were much more successful on solving algorithmic items. Half of the students with high algorithmic performance had low conceptual performance. The current emphasis on algorithmic problem solving does not adequately prepare students with the conceptual understanding they need to reason in chemistry.

Theoretical and Methodological Approaches

Although chemists require quantitative calculations and a deep understanding of representations and notational systems, current instruction fails to connect the "calculations" of chemistry with their use in authentic chemistry practices. For instance, a study by Evans, Leinhardt, Karabinos, and Yaron (2006) found that the primary aims for practicing chemists are to explain phenomena, analyze substances to reveal their chemical make up and synthesize new materials. However, Evans found that textbooks focused equally on explanation and calculations with little coverage of analysis or synthesis activities. This large disconnect between authentic practice and the content of typical chemistry instruction suggests that many students fail to acquire a realistic sense of chemistry as a domain. When learning is disconnected from intellectual and practical use, the knowledge is not readily accessible, and not very memorable or robust across applications (e.g., Bransford, Brown, & Cocking, 2000).

The design of the embedded formative assessment modules for the ChemCollective Virtual Lab embodies what has been learned from cognitive and educational measurement research about the power of quizzing and formative assessment for learning. Pashler et al., 2007 cites multiple studies showing that quizzing helps students to remember key information over longer periods (e.g., Roediger & Karpicke, 2006). Further, Black and Wiliam (1998) suggested that effective formative assessment that provides "short term feedback so that obstacles can be identified and tackled" (Black, 1998) produces effect sizes ranging between .4 and .7. Our embedded formative assessments deliver just-in-time coaching as students undertake the activities. Similar

Davenport, J. L., Rafferty, A., Timms, M. J., Yaron, D. & Karabinos, M (2012). ChemVLab+: Evaluating a Virtual Lab Tutor for High School Chemistry. *The Proceedings of the 2012 International Conference of the Learning Sciences.*

contingent coaching that includes explanations has been shown to promote student achievement (Bangert-Drowns et al., 1991; Dassa et al., 1993).

We hypothesized that the combination of formative assessment with the ability of the ChemCollective Virtual Lab to engage students in meaningful problem solving in chemistry will enhance student learning of complex chemistry concepts. We explored student engagement and learning by using a mixed-methods approach that involved classroom observations, pretests and posttests, log file analyses, and teacher interviews.

Method

Participants

Sixty-nine students from three classrooms at two California high schools completed the online chemistry modules as part of normal classroom instruction.

Design and Procedures

Students individually completed pretests during the class period before the activities began. Over the next three to four class sessions, two researchers performed classroom observations as students completed three online chemistry modules working either alone or in pairs. Computer log files recorded all student actions on the computer activities. After completing all three modules, students individually completed the posttest.

Materials

ChemVlab+ Activities

Three online activities included intelligent tutoring and served as learning materials with embedded formative assessments. All activities addressed core issues in stoichiometry (i.e., the relationship between relative quantities of reactants and products in chemical reactions) and the central idea of conservation of matter. Each activity consisted of a series of tasks in an authentic context that exposed students to techniques and tools in analytic chemistry.

The first stoichiometry activity focused on the issues of concentration and dilution in the context of preparing drinks with differing concentrations. Students completed interactive activities to sort drinks according to concentration, used a spectrometer in the virtual lab to determine concentration, and created solutions with specified concentrations. The second activity focused on the concepts of dilution and molar mass as students determined which factories along a river were polluting. Students determined the molar masses of different compounds and used the virtual lab to create dilutions and evaluate the water samples. Finally, the third activity focused on balancing chemical equations and using stoichiometry to determine unknown entities as students used the analytic technique of gravimetric analysis to determine whether samples of drinking water met EPA guidelines. Students used the virtual lab to determine which reactions formed precipitates, balanced chemical equations, and carried out inquiry to evaluate the concentration of sulfates in water. See Figure 1.

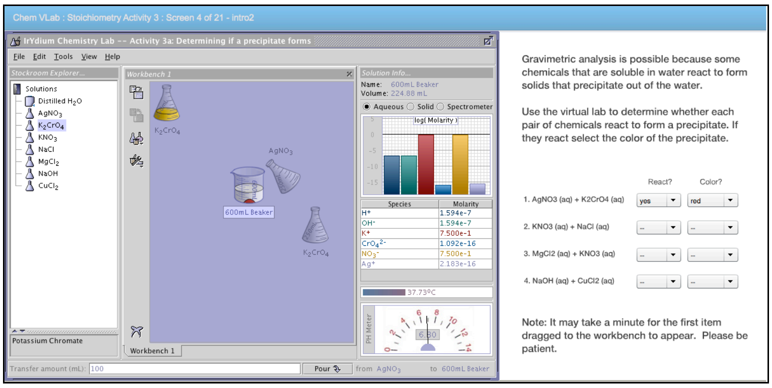

Figure 1. Students combine chemicals in the virtual lab to determine how the chemicals react.

Embedded formative assessments and Tutoring

Prior studies using the ChemCollective virtual lab environment suggested that many students spent a lot of time unsure of what action to take. To keep students in the zone of proximal development (Vygotsky, 1978), where students are challenged, but not bored or frustrated, the activities offered tutoring to students when they clicked the HINT button or attempted to move on with incorrect responses. Feedback appeared as a dialog box that provided information about the nature of the error, and visual elements that highlighted areas for students to attend to. See Figure 2.

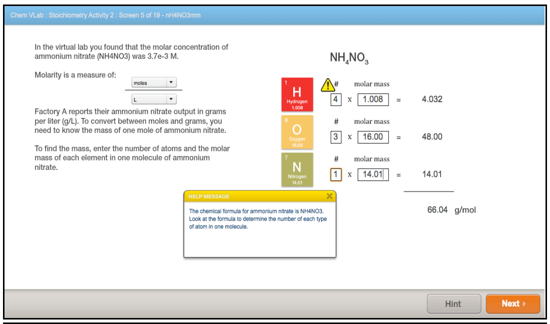

Figure 2. Example of hint messages in activity 3.

As our embedded formative assessment modules included a range of activities in open-ended environments, we used constraint-based modeling (CBM) to identify errors using logic that allowed students the freedom to use a variety of strategies (Mitrovic, 1994; Ohlsson, 1994). The logic that underlies our hinting was created based on data mining of detailed log files of 450 college students solving problems using the ChemCollective virtual lab. The constraints produced tutoring that breaks down larger problems into subgoals. Feedback was graduated and ranged from simple prompting to think about the rule or concept that applies, to reminding them of the applicable rule or concept, to showing them how the rule or concept is used to solve the problem. As a simple case, in the example above the system uses logic to determine whether a student has typed in the appropriate numbers for each atom in order to calculate the atomic mass. The first time a student makes an error, the system flags the error by through a visual indicator of where the mistake occurred (the triangle with exclamation point) and a message appears that the student can click the triangle indicator for additional help. The next level of help gives the student the "rule" for how to approach the problem. In this case, the message would state, "The chemical formula for ammonium nitrate is NH_4NO_3. Look at the formula to determine the number of each type of atom in the molecule." Finally, if the student requires the maximum level of help, the message student receives the prompt that "The chemical formula of ammonium nitrate is NH4NO3. In each molecule of ammonium nitrate there are 4 atoms of hydrogen, 3 atoms of oxygen and 2 atoms of nitrogen. Please put the correct values in the highlighted boxes."

Data Analysis

We used a mixed-methods approach to evaluate whether the online chemistry activities promoted student engagement and learning. We analyzed data from four sources: classroom observations, pre and posttest results, computer logs and teacher interviews. To ensure that students were actively engaged in the activities, two researchers conducted classroom observations as the students completed the assessments. To measure student learning as a result of the activities, students completed a pretest before completing the three chemistry activities and completed the same test as a posttest. The pre-post measure consisted of both researcher developed items as well as items from released versions of the American Chemical Society exam. To measure student learning during the activities, we analyzed the log files. As the activities were designed to give students multiple opportunities to practice the same skills, evaluated the log data generated by the online activities to determine whether students made fewer errors over time on similar items. Finally, to establish whether teachers found the activities to be usable and feasible for classroom use, we carried out teacher interviews with the two participating teachers.

Results

Classroom Observations

The classroom observations revealed that students spend the majority of time engaged and on-task as they completed the activities. Overall, student conversation was related to the chemistry activities. The observations also revealed usability issues of the software and tutoring. During the first activity, a number of students had difficulty pouring and finding glassware in the virtual lab. However, students rapidly learned to use the interface and did not have subsequent problems on the following activities. Further, two hints related to molar mass were not interpreted by the students in the way we expected. We use these data to iteratively refine the activities and will conduct another round of classroom tests throughout the 2011-2012 school year.

Pre-Post Test Analyses

As one indicator of student learning from the ChemVLab+ activities, all students took a pretest and a posttest. A paired-samples t-test comparing student pre and posttest scores found that students posttest scores (M= 16.8, SD=5.2) were significantly higher than their pretest scores (M= 15.4, SD=4.8), t(68) =3.7, p = .001. The Cohen's d effect size for this analysis was .28.

Log file analyses

In addition to the pre-post test measures, we also investigated whether the process data provided evidence of student learning throughout the activities. Our activities with intelligent tutoring provided increasing amounts of help until students correctly complete each part of the activity. Data mining the log files generated by students using the chemistry virtual labs, we were able to investigate whether students learned during the activities themselves. Here we provide two examples that demonstrate student behavior shifting over the course of a single activity.

Activity 1: Matching Concentrations

In activity 1, students were asked to create drinks by adding water and a drink mix to match the concentration of another student's drink. In the activity, students were first provided scaffolds in the prompt as they matched the concentration of Diego's drink, later in the activity they were asked to match the concentration of Mia's drink. A prototypical strategy for solving this problem is to add a fixed amount of water to a vessel and to slowly add the drink mix until the concentration (as measured by the spectrometer) matches the desired concentration. A detailed analysis of the log files reveals student learning as they progressed through the activity. Initially, despite scaffolding in the prompt, students struggled to match the concentration of Diego's drink. Only 24% of the students were able to match the concentration using a single vessel, and the log files revealed many exploratory and incorrect behaviors in the virtual lab. For instance, rather than adding additional water when the concentration exceeded what was desired, many students abandoned the flasks and started again. Further, 25% of students continued to add mix to flasks that already exceeded the desired concentrations. With the automated feedback and tutoring, all students were eventually able to create the correct concentration.

Performance on a subsequent parallel task, to match the concentration of Mia's drink, suggests that students learned over the course of the assessment. In finding Mia's concentration 61% of students (compared with 24% for the previous task) came up with the prototypical solution of matching the concentration using a single vessel. Further, students were less likely to make errors such as persisting in adding drink mix to a vessel that exceeded the desired concentration. Overall, only 10% of abandoned vessels exceeded the desired concentration (compared with 23% in the prior task). Taken together, the log file analyses suggest that students applied their learning from the tutoring on prior screens to modify their behaviors.

Activity 2: Making Dilutions

A detailed log file analysis of activity 2 also provides evidence of student learning in the course of the activity. In activity 2 students were first asked to make a dilution of 2:1, and later asked to make a dilution of 6:1. In the first task, to make a 2:1 dilution, the log files revealed a range of error types. Many students (63%) failed to take into account the volume of the beakers; 46% of students attempted to pour more liquid in a beaker than it could hold. A number of students, 27% (including some over-pourers) attempted to pour more liquid out of a vessel than actually existed.

In a dilution, there is an amount of substance (the chemical you care about) in a solution (typically water). Thus to make a 1:2 dilution, the students must consider the amount of substance in 1 part water, compared with the same amount of substance in 2 parts water. The correct answer is to double the current volume of the solution by adding equal parts water and the to-be-diluted sample. In contrast, 37% of students erroneously poured in twice as much water as the sample.

The second task, to make a more complex 6:1 dilution revealed significant student learning. Students made fewer mistakes related to the volume of the vessels with only 30% of students attempting to overpour (compared with 63% in the previous task). Further, 89% of students made a correct dilution by pouring the water and sample only once; and those that did not generally poured the sample once and the water multiple times. This pouring behavior was more focused than on the previous dilution as shown by the number of prototypical solutions. In general, students were given less scaffolding in the prompt and required fewer hints to get the correct solution, showing they had modified their behavior based on the prior task.

Teacher Interviews

After the classroom observations were complete, researchers carried out teacher interviews with the two participating teachers to gauge their overall reaction to the activities and establish the usability and feasibility of the assessments. Both teachers responded very positively to the ChemVLab+ activities and planned to use them again with their classes. Teachers said they thought the activities "made sure students were learning the material instead of going through the motions," that "the students were really involved" and that the activities were a "good challenge." Further, the teachers felt the intelligent tutoring was good at identifying student errors and offering guidance. For instance, on teacher said, "Kids that normally have trouble with unit conversions and molar mass still had trouble in the lab. But the lab does a good job hand-holding them and showing them how to do it." Finally, the teachers said their students enjoyed the problem solving contexts. Students "liked using the real settings and tying the chemistry to new contexts." Overall, the reactions of the teachers suggest that the ChemVlab+ activities were usable and feasible for classroom use.

Significance and Conclusions

Our project's goals are to create and test activities that teach and assess core ideas in chemistry while providing students the opportunity to carryout open-ended investigations and make connections between microscopic, macroscopic and quantitative representations. Findings from our field test suggest that the activities promoted student engagement and learning of chemistry concepts. Classroom observation data suggested that the majority of students were actively engaged and "on topic" as they worked through the activities. Students' scores were significantly higher on the posttest than on the pretest, suggesting overall learning gains as a result of the activities. Analyses of student process data from the computer log files suggest that students make fewer errors on subsequent items that address similar skills as they work through the ChemVlab+ activities. Finally, teacher interviews suggest that our system is usable, feasible, and considered worthwhile

The ChemVlab+ activities embody the key features of formative assessment with feedback and coaching, realistic problem contexts, and activities that allow students to connect multiple representations and explore the same concepts in a variety of contexts. Our results provide preliminary evidence that using research-based design principles to create interactive online activities improves student understanding of difficult scientific concepts. Further, our mixed-methods approach provides a range of data that allow us to capture student engagement and learning over the course of the activities, as well as after the activities were completed.

The current work demonstrates that it is possible to provide effective intelligent tutoring for activities in an open-ended simulation environment. Further, our mixed-methods approach provides a framework for the evaluation of intelligent tutors that tackle complex subjects.

The research reported here was supported by the Institute of Education Sciences, U.S. Department of Education, through Grant R305A100069 to WestEd. The opinions expressed are those of the authors and do not represent views of the Institute or the U.S. Department of Education.

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