Immersive Chemistry Video Game

Carlos Morales
Kermin Martínez-Hernández
Gabriela Weaver
Ryan Pedela
Kellen Maicher
Eugene Elkin
Doug Danforth
Naveen Nattam

Purdue University

Abstract

A team at Purdue University has been working on a NSF sponsored project to create a set of research-validated recommendations for the development of science video games. As a way to accomplish this task, the team created a three-dimensional first-person shooter video game that requires players to utilize chemistry knowledge to advance in the game-world. A team of chemistry, computer graphics technology, computer science, and instructional designers collaborated in the development of the game and in conducting the research. This paper details the process used by the team. Results from human subject testing will be presented at the conference.

CR Categories: I.3.6 [Computer Graphics]: Methodology and Techniques— Interaction Techniques; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation

Keywords: game development, instructional games, pedagogical games

1 Introduction and Background

The goal of our project is to indentify the the motivational and educational issues that influence the creation of pedagogical video games. Specifically, this project aims to create educational games that have the immersive and game-play qualities of traditional entertainment video games.

The use of digital games has grown exponentially since the early 1980's, when personal computers first appeared. Pong, the first commercial video game, became available in 1974. The oldest of today's traditional college students wasn't born until 1981, a full 7 years later, the year that the IBM PC was introduced [Prensky, 2001]. The now ubiquitous nature of computers and computing-capable devices has resulted in making digital environments easily accessible. As a result, there is a generation of people who have grown up not knowing a world without computers, and who have been shaped, possibly in fundamental ways, by access to the tools provided by this digital environment.

Prensky [2001] argues that the current generation of students has a degree of experience with computer games that makes them different as learners than prior generations of students, including their teachers. Research in neuroplasticity [Shaw and McEachern, 2001; Sterr, et al., 2002; Merzenich, et al., 2002; Celnik and Cohen, 2003] supported by studies in brain imaging [Rapoport, 1999] would indicate that it is highly likely that the regular and frequent use of video games and digital multimedia environments by today's students could result in brain organization that is different from that of older, non-game players.

A number of studies have suggested cognitive effects from computer game playing. A recent paper by Green and Bavelier [2003] shows that video-game players outperform non-video-game players on tasks of visual attention capacity, enumeration, and attentional "blink" time. Furthermore, non-video-game players who then trained with videogames for as little as 10 hours were able to demonstrate significant improvements on these performance measures. It has been suggested that the average teenager in America today plays video games for 90 minutes per day [Prensky, 2001]. It seems plausible, then, that students in today's classrooms would be capable of processing information presented to them very differently than in the verbal, conceptually linear approach that is still a dominant mode of pedagogy. Today's students may even learn more effectively if material were presented in a manner that takes advantage of their facility with digital environments and, in particular, with digital game environments.

Hitendra Pillay [2003] reported on a study to examine the effects that computer game playing has on computer-based instructional tasks. The findings suggest that playing recreational computer games had a positive effect on subsequent performance on computer-based instructional tasks. Furthermore, the type of computer game played by the students influenced the choice of cognitive strategies they used for the instructional tasks. This type of skill transfer would be a strength for students if instructional material shared some of the characteristics of the games these students are accustomed to playing. The use of computer games appears to result in enhanced thinking abilities such as inductive reasoning [Camaioni, et al., 1990], creativity [Doolittle 1995], anticipatory thinking, means-end analysis and parallel processing of information [Pillay, 2003], all of which are desirable cognitive skills for problem-solving in general, and particularly in science. Structural information is the formatting, layout and design of a digital environment and is independent of content but provides the basis for dealing with the content [Mayer and Sims, 1994]. Similarities in structural information between games and instructional materials would assist in the skills transfer that would then help students perform better on instructional tasks [Pillay 2003, Spiro and Jehng, 1990].

The cognitive theory of multimedia learning proposed by Mayer [2001, 2002] suggests that there are important characteristics of multimedia environments that may contribute to learning at a deeper level. This cognitive theory is based on the idea that human beings possess dual channels for processing visual and auditory information. By presenting a combination of spoken words (auditory information) with images (visual information) the cognitive processes are used most effectively and result in an integrated model of the material learned that can be accessed

[1] {morales | gweaver | maicher | ddanfort | kmartine | pedela | eelkin | nnattam }@purdue.edu

either through visual or verbal memory modes. On the other hand, when text is presented in a written form it competes with graphical information and, based on Mayer's "limited capacity assumption" for each channel, there will be a less efficient use of the visual channel in the formulation of a mental model. Mayer further asserts [2001, 2002] that active processing must take place for meaningful learning to occur and for the student to construct mental models or "knowledge structures." Active processing involves paying attention to incoming information, and organizing and integrating that information. This aspect of the cognitive theory of multimedia learning has parallels with the constructivist theory of learning [Bodner, 1986; Bunce, 2001], which states that knowledge must be actively constructed by the learner, not simply transferred into the learner's mind. Whether by Mayer's active processing or through a constructivist standpoint, these theories both indicate that active involvement of the learner in the educational task is a critical component for meaningful learning to occur.

While the benefits of using computer games for education are known, the majority of the instructional video games do not place the same level of emphasis on game-play issues and realistic graphics as commercial games. An article in the Journal of Chemical Education [Russell, 1999] lists 67 games for teaching chemistry. The majority of these are simply creative adaptations of drill-and-practice tutorials or applications of facts in algorithmic ways.

The factors that often differentiate commercial games from edutainment products are the emphasis on game-play issues and the immersiveness of the environment, in terms of graphics and storyline, present in commercial games. In many games, the rules must be easy to learn but the game itself must be difficult to master, thus maintaining challenge. But the challenge itself must also be highly adaptive, allowing players at a variety of levels to be engaged without being overwhelmed. Frequent rewards are also necessary to keep the player involved, as well as a clear overall vision that allows the player to set goals and stay focused. Other game elements that are believed to be important in maintaining user interest include competition/challenge, rules, goals/objectives, outcomes and feedback, interaction, and story [Amory, et al., 1999; Prensky, 2001; Smith and Chabay, 1977]. Edutainment games typically focus almost entirely on the delivery of instructional content from a "fun perspective." The net result is that edutainment products do no enjoy the same level of usage as commercial games.

These differences can partially be attributed to differences in resources and skill sets available to developers. Commercial games are routinely created by teams of ten people or more with skills with a wide variety of skills over a period of two to three years.

To effectively integrate commercial game development with instructional delivery, there needs to be a solid theoretical foundation driving the process. Starting in June 1993, Co-PI Weaver started to conduct studies in this area. Thirty-four undergraduate students have been studied during their use of games, 15 males and 19 females. These students were volunteer participants from a variety of different majors in science, engineering, agriculture, pharmacy and liberal arts. Seven games were used for the study, each of a different genre: strategy, puzzle/adventure, role-playing, simulation, action/first-person shooter. The game Chemicus was included among the games tested, which is of the puzzle genre, but there was another commercial game of this same type that was included in the testing in order to control for the fact that Chemicus is intended to be an educational game, whereas the others are not. Student were given a survey about various aspects of the games. They answered the survey once after having played the game for one hour, and then again after having played the game for six hours (the maximum amount of time that any game was played in this study, with all game play in 1-2 hour sessions). Students were being observed the entire time that they were playing the games in order to look for patterns in behavior and to rate their mastery of the games.

2 Implementation

In the course of pursuing our research goals, our team elected to create a 3D first-person shooter game to teach Chemistry concepts. The game was created using a production process in which game designers, artists, programmers, and subject matter experts colloboratively build games. The project was implemented using a production process similar to that found in commercial entertainment game production companies. Co-pi Morales relied on his experiences from working at High Voltage Software to guide the production process used in this game. The pre-production phase of the project presented a unique set of challenges not typically tackled by instructional-designers or commercial entertainment game developers.

At a high-level, this project can be viewed as the integration of instructional-design and commercial entertainment game production practices. At an operational level, properly integrating these two different workflows turned out to be a tremendous challenge. Our ultimate goal was to create an educational game in which the educational elements of the game are fully integrated the narrative of the game. Thus, all of the educational challenges needed to be shown through the lens of the game narrative and motivated by game-play elements.

Our initial attempts yielded scenarios where it was evident to the player that a back-story had been constructed and then laced with instructional challenges created by subject matter experts (SME). This not only created a poorly constructed game in terms of immersiveness, but also was also not very instructional. Fixing this aspect of our production process turned out to be more difficult than any of the technical challenges we faced.

To overcome this problem, we reorganized the design team in a manner that forced the chemistry SME and game-designers to collaboratively create guidelines for the operational aspects of the game. The Chemisty SME primarily concentrated on the educational aspects of the game and the game-designer concentrated on the game-play and narrative components. Prior to this arrangement these groups primarily worked in isolation and only came together to integrate their parts. Under the new arrangement, they created all of their parts collaboratively. Initially, this slowed down production because there was a tremendous amount of cross-education between these two groups. However, the quality of the game design created by the team improved significantly. Figure 1 shows the organization of the design related teams.

The Chemistry team started out by narrowing possible learning-activities to those documented in the educational literature to evoke misconceptions on the part of the students. Initially, this led the Chemistry team to concepts of chemical-equilibrium, stoichiometry, and numerous other possibilities. To fit into the narrative aspects of the game, the chemistry team elected to always present the chemistry challenges in a way that had a practical application. In one part of the game, the characters need to make ammonia to allow them to grow food. This was a perfect place to introduce the concept of stoichiometry through a practical challenge that forced the players to use the Haber-Bosch process to synthesize ammonia. Another challenge within the game forces the player to deal with acids and bases as the game narrative places the player in a situation where he/she needs to deal with sewage in a waste-water facility.

To better focus the design team on the functional aspects of the game, we transferred the responsibility for establishing the visual aspect of the game to a concept artist outside of the team. This allowed the team to concentrate on the elements needed for instructional effectiveness and for the game to be fun. This arrangement also improved the quality of the product generated by each of the groups.

Under the original team arrangement, the design team was forced to supply all of the necessary materials needed by the artists and programmers to create the game. This was disastrous and inefficient. Many times we would not catch major flaws in the game until after the production teams had completed their work. These difficulties were primarily due to the fact that the game design materials were heavily text-oriented and lacked the level of visual detail needed for the production team to plow through the asset creation stage. Specifically we found that many visual elements needed to solve the chemistry challenges were missing, control elements were often constructed in a way that was not intuitive to the player, or the chemistry was not presented in a manner congruent with the game world.

The placement of an independent concept art team between the design team and the production teams, fixed our problems. This team created detailed 2D renderings and 3D mockups that would serve as a reference for the production teams. Two dimensional images were primarily used to provide a sense of overall look and style to the 3D artists and programmers of the production team. While they were useful in describing the general look and feel of the game, problems developed when complex objects of specific detail needed to be created in three dimensions. While the 2D depictions provided large quantities of visual information, 3D artists worked more effectively with views of objects at several angles in the modeling process. This was initially addressed by providing 2D orthographic views of objects at various vantage points, but the sheer number and complexity of objects that were required to be rendered made this an inefficient method. To further speed up the pace of concept-art production, the concept art team elected to do some of the mock up work using Last Software SketchUP.

We also added a review panel of non-game players composed primarily of female students to help guide the development of the game environment and activities. This was necessary because our production team did not match the demographics our target audience. While we wanted to the game to appeal to both males and females, the production team was composed primarily of males. During the testing of some of the levels, we found that our choices for game-play elements and art were not effective at engaging females and non-game-players.

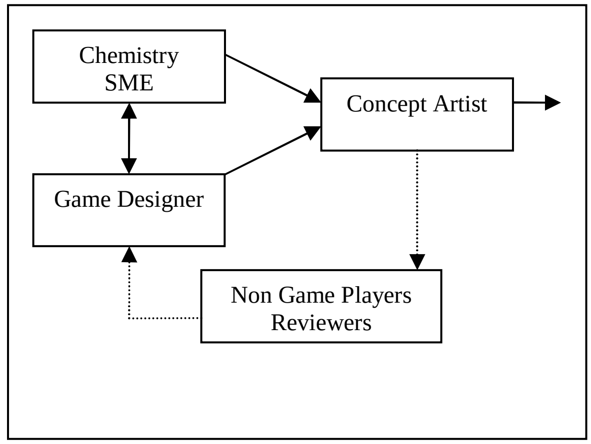

Figure 1: Design Team Organization

3 Production

The production of the game was implemented using a similar process as that found at commercial entertainment game companies. There were three primary production teams composed of artists, programmers, and technical artists/directors.

The programming team, led by Ryan Pedela, was responsible for the programming of the actual game and the creation of any custom tools necessary to improve the software development process. Individuals within the team took on the responsibility of writing code for artificial intelligence, graphics, networking, data tracking, and game play programming.

With the exception of the assessment and data-tracking aspects of the game, the development activities of the programming team were fairly standard for game development. An interesting challenge faced by the team was the inclusion of game-play features that could be toggled on/off during the testing phase of the game. In order for the research team to be able to isolate the features of game design that makes an immersive game, it was important to build into the game the technological ability to turn features on/off. From a programmer's perspective, this was implemented through the inclusion of game-cheats via the game console.

In addition to the ability to toggle features on/off based on research requirement, the programming team was also faced with the challenge of building a data collection and analysis feature into the game. While data collection instruments outside of the game environment would allow the research team to discover affective and performance discoveries about the game experience, we wanted to enable the game to expose data in manner that would allow deeper types of discovery. One possible research inquiry included tracking the communication patterns of the players in a multiplayer adversarial scenario versus a multiplayer collaborative scenario. From a software development perspective, this created two challenges. First, we needed to track a large amount of data without having a significant impact on the performance of the game. Two possibilities examined by the team included dumping the data to a file on the local hard drive or to create a socket connection to a secondary computer for archival and analysis. Both of these presented their own benefits and problems. As of this writing, the team has not selected a solution to this problem.

The second challenge created by this scenario was need for data analysis tools for examining the data. If the analysis is to be done in-game, the programming team bears the responsibility of creating these tools. On the other hand, if the analysis of the data is done after the game-play concludes then the data analysis can be done using standard experimental design tools. As of this writing, the team is examining the use of both approaches. In scenarios, where we would like to change aspects of the player's in-game experience based on research constructs, then the data analysis needs to be implemented within the actual game.

4 Art Production and Technical Artists

While the production requirements for the project required the art team to be extremely large, this team did not face any significant challenges unusual for a game development team. The team was led by Eugene Elkin and consisted of modelers, animators, motion-capture specialists, texture artists, and user interface (UI) artists. The 3D assets were created in Max or Maya, depending on the preference of the individual artist. Textures and UI elements were created with Photoshop. The motion-capture sessions were conducted at the Purdue University Envision Center using a optical-motion capture system and were applied using MotionBuilder. Figure 2 shows one of the in-game characters created by the art team.

Figure 2: Game character

The technical artist team was primarily responsible for creating in-house tools to speed up art production or to facilitate the placement of art assets into the game engine. The most time consuming portion of this project was the creation of art assets. Thus, any tools or techniques created by the technical artists or technical directors had a significant impact on the pace of asset creation.

One scenario that illustrates the impact of this team on the success of the project was the game-asset-export cycle. At the beginning of the project, each of the models were individually exported and placed into the game engine by the programmers. The process was accurate but very slow. One of our technical directors wrote a script that allows the artists to create levels within Max. When the artists is done, the script takes each object, moves it to the origin of the world, exports it as an individual .X file, and writes to a text file an inventory of all of the exported objects. This single script reduced the amount of time that it typically took the team to place objects in a scene by a factor of eight. Tools such as this one have been invaluable to the success of the project.

5 Evaluation and Conclusion

To properly evaluate the project the team imposed a series of formative and summative evaluation mechanisms. The process used to create and deploy a game level is fairly lengthy and involves many people. First, the chemistry and design teams formulate the educational and non-educational challenges. Those challenges are then visualized by a team of concepts artists. The art assets are then created by tens of artists using the functional instructions provided by the design team and the visualization created by the concept-art team. Then, those art assets are placed into the game code by the programmers.

This long chain of interdependent processes can result in a product that does not deliver on the original design. To compensate for this possibility, numerous formative evaluation mechanisms were used. The first mechanism was to include a review process in which the work of all of the teams is reviewed by the previous team in the chain. The design team reviews the work of the concept-art team, the concept-art team reviews the work from the art-team, etc. This process allowed us to make mid-production changes without incurring tremendous production time losses.

The most potent method for formative evaluation came in the form of game-play testing. In this type of evaluation, members from the target population for the game were given the opportunity to play the game. As they played the game, members from the production team observed their behavior and noted any difficulties they had in completing the needed tasks. During this type of testing the objective is to provide the production team with input on the effectiveness of their design choices. It is important to note that this type of evaluation cannot provide validation on the instructional effectiveness of the game. It is not possible to assert that the players are learning from the game using this mechanism. However, the mechanism is very important in validating the mechanics of the game. We can validate things like the visibility of in-game text, the intuitiveness of game controls, etc. We found each game-play testing phase to be extremely valuable.

After the game-levels went through a game-testing phase, the game was tweaked and entered summative testing to validate the instructional effectiveness of the game. The objective at this point is to test if exposure to the game makes a significant change in the learner's performance or attitudes. As of this writing, the game is under going this evaluation. Results will be presented at ACM SIGGRAPH 2006.

Developing a solid educational game that is both sound pedagogically and entertaining requires a design process that integrates educational issues with the traditional game design process. In this project we have found that the integration of artists, programmers, game-designers, concept artists, and subject matter experts has been invaluable in meeting that goal.

References

AMORY, A., NAICKER, K., VINCENT, J. AND ADAMS, C. (1999). The use of computer games as an educational tool: identification of appropriate game types and game elements. British Journal of Educational Technology. 30(4), 311-321.

ARASASINGHAM ET AL. (in press). Assessing the Effect of Web-Based Learning Tools on Student Understanding of Stoichiometry Using Knowledge Space Theory, Journal of Chemical Education.

ARNOLD, L. J. (1992). Mass spectra and the Macintosh isotope pattern calculator: A program to calculate isotopic ratios for molecular fragments. Journal of Chemical Education. 69, 811.

BANKS, A. J., HOLMES J. L., KOTZ, J. C., YOUNG, S., SCHATZ, P. F., AND MOORE, J. W. (1997). Periodic Table Live! Journal of Chemical Education. 74, 445.

BIRK, J. P. AND KURTZ, M. J. (1999). Effect of experience on retention and elimination of misconceptions about molecular structure and bonding. Journal of Chemical Education. 76(1), 124-128.

BODNER, G. M. (1986). Constructivism: A Theory of Knowledge, Journal of Chemical Education, 63, 873-878.

BUNCE, D. M. (2001). Does Piaget still have anything to say to chemists? J. Chem. Educ. 78(8), 1107-1121.

BUNCE, D. M., GABEL, D., SAMUEL, J. (1991). Enhancing Chemistry Problem-Solving Achievement Using Problem Categorization. Journal of Research in Science Teaching. 28(6) 505-522.

CAMAIONI, L., ERCOLANI, A. P., PERRUCCHINI, P., AND GREENFEILD, P. M., (1990). Video games and cognitive ability: The transfer hypothesis. Italian Journal of Psychology. 17(2), 331-348.

CELNIK, P. AND COHEN, L. G. (2003). Functional relevance of cortical plasticity. In Boniface, S. and Ziemann, U. (Eds.), Plasticity in the human nervous system: Investigation with transcranial magnetic stimulation. New York: Cambridge University Press.

CHASTEEN, T. G. (2001). News from online: Teachng with chemical instrumentation on the web. Journal of Chemical Education. 78(9), 1144-1148.

CHEN, C. (1999). A protocol analysis model for investigating computer supported problem-solving activities. Office Systems Research Journal. 17(2), 35-43.

COLLIS, B. A., KNEZEK, K-W. L., et al. (1996). Children and Computers in School. New Jersey: Lawrence Erlbaum.

DOOLITTLE, JOHN H. (1995). Using riddles and interactive computer games to teach problem-solving skills.Teaching of Psychology. 22(1), 33-36.

FURIO, C., CALATAYUD, M. L., BARCENAS, S. L., AND PADILLA, O. M. (2000). Functional fixedness and functional reduction as common sense reasonings in chemical equilibrium and in geometry and polarity of molecules. Science Education. 84, 545-565.

GABEL, D., (1999). Improving teaching and learning through chemistry education research: A look to the future. Journal of Chemical Education, 76, 548-554.

GILLESPIE, R. J., SPENCER, J. N. AND MOOG, R. S. (1996). Bonding and molecular geometry without orbitals – the electron domain model. Journal of Chemical Education. 73, 622- 626.

GRANATH, P. L. AND RUSSELL, J. V. (1999). Using games to teach chemistry: 1. The Old Prof card game. Journal of Chemical Education. 76(4), 485-486.

GREEN, C. S. AND BAVELIER, D. (2003). Action video game modifies visual selective attention. Nature. 423, 534-537.

HARP, S. F. AND MAYER, R. E. (1997). The role of interest in learning from scientific text and illustrations: On the distinction between emotional interest and cognitive interest. Journal of Educational Psychology. 89(1), 92-102.

HEUREKA-KLETT (2002). Chemicus. Berlin: Tivola Publishing. Holman, R. W. (2001). Organic CD, version 3.00. Journal of Chemical Education. 78(12), 1603.

JCE SOFTWARE (2003). Software listing at the Journal of Chemical Education, http://www.jce.divched.org/JCESoft/index.html.

JACOBSEN, J. J. AND MOORE, J. W. (2000). Chemistry Comes Alive! Volumes 1 and 2. Journal of Chemical Education. 77(5), 671-672.

JACOBSON, M. J. AND SPIRO, R. J. (1995). Hypertext learning environments, cognitive flexibility, and the transfer of complex knowledge: an empirical investigation. Journal of Educational Computing Research, 12, 301-333.

KATZ, R. N. (1999). Dancing with the Devil: Information Technology and the New Competition in Higher Education. San Francisco: Jossey-Bass, 1999.

KELLY, G. J. AND CRAWFORD, T. (1996). Students' interaction with computer representations: Analysis of discourse in laboratory groups. Journal of Research in Science Teaching, 33, 693-707.

KEMP, K. C. (1988). A novel, simple and inexpensive model for teaching VSEPR theory. Journal of Chemical Education. 65(3), 222.

KOTZ, J. C. AND TREICHEL, P. M. (2003). Chemistry and Chemical Reactivity, 5th ed., Thomson and Brooks/Cole.

KOTZ, J. C. AND YOUNG, S. (1995) Chemistry Navigator. Journal of Chemical Education Software. 6C2.

KOZMA, R. B. (1991). Learning with media. Review of Educational Research, 61, 179- 211.

MARKHAM, J. R. (1998). Flying over atoms CD-ROM. Journal of Chemical Education. 75, 247.

MARTINEZ-JIMENEZ, P., PONTES-PEDRAJAS, A., CLIMENT-BELLIDO, M. S., AND POLO, J. (2003). Learning in chemistry with virtual laboratorios. J. Chemical Education. 80(3), 346-352.

MAYER, R. E. (2001). Multimedia Learning. Cambridge, England: Cambridge University Press.

MAYER, R. E. (2002). Cognitive theory and the design of multimedia instruction: An example of the two-way Street between cognition and instruction. New Directions for Teaching and Learning. 89, 55-71.

MAYER, R.E. AND SIMS, V. K. (1994). For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. Journal of Educational Psychology, 86(3), 389-401.

MABROUK, P. A. (1996). An exciting approach to student learning in analytical chemistry: It's Jeopardy! The Chemical Educator. 1(3).

MCKENNA A. G. AND MCKENNA, J. F. (1984). Teaching VSEPR theory: The dilemma of five-coordination. Journal of Chemical Education. 61(9), 771-773.

MERZENICH, M. M., WRIGHT, B. A., JENKINS, W., XERRI, C., BYL, N., MILLER, S., AND TALLAL, P. (2002). Cortical plasticity underlying perceptual, motor, and cognitive skill development: Implications for neurorehabilitation. In Johnson, M. H. and Munakata, Y. (Eds.), Brain development and cognition: A reader. Malden, MA: Blackwell Publishers.

NAKHLEH, M. B. AND KRAJCIK, J. S. (1993). A protocol analysis of the influence of technology on students' actions. Verbal commentary and thought processes during the performance of acid-base titrations.

NOH, T. AND SCHARMANN, L. C. (1997). Instructional influence of a molecular-level pictorial presentation of matter on students' conceptions and problem-solving ability. Journal of Research in Science Teaching, 34, 199-217.

PAULISSE, K. W. AND POLIK, W. F. (1999). Use of WWW discussion boards in chemistry education. Journal of Chemical Education, 76, 704-708.

RAGHAVAN, K., SARTORIS, M. L., AND GLASER, R. (1998). Why does it go up? The impact of the MARS curriculum as revealed through changes in student explanations of a helium balloon. Journal of Research in Science Teaching, 35, 547-567.

ROBERTS, R. M. AND TRAYNHAM, J. G. (1976). Molecular geometry: As easy as blowing up balloons. Journal of Chemical Education. 53(4), 233-234.

PAIVA, J. C. M., GIL, V. M. S., AND CORREIA, A. F. (2003). Le Chat: Simulation in Chemical Equilibrium. Journal of Chemical Education. 80(1), 111.

PARKER, J. (1997). VSEPR theory demo. Journal of Chemical Education. 74(7), 776.

PARRILL, A. L. AND GERVAY, J. (1996). The stereochem game: Making chemistry more fun. The Chemical Educator. 1(5).

PAULISSE, K. W. AND POLIK, W. F. (1999). Use of WWW discussion boards in chemistry education. Journal of Chemical Education, 76, 704-708.

PENCE, L. E. (1999). Cooperative electronic email: Effective communication technology for introductory chemistry. Journal of Chemical Education, 76, 697-698.

PFENNIG, B. W. AND FROCK, R. L. (1999). The use of molecular modeling and VSEPR theory in the undergraduate curriculum to predict the three-dimensional structure of molecules. Journal of Chemical Education. 76(7), 1018-1022.

PIERONI, O. I., VUANO, B. M. AND CIOLINO, A. E. (2000). Classroom innovation: Games to make chemistry more interesting and fun. The Chemical Educator. 5, 167-170.

PILLAY, H. (2003). An investigation of cognitive processes engaged in by recreational computer game players: Implications for skills of the future. Journal of Research on Technology in Education. 34 (3), 336-350.

PRENSKY, M. (2001). Digital Game-based Learning. New York: McGraw-Hill.

RAPOPORT, S. I. (1999). How did the human brain evolve? A proposal based on new evidence from in vivo brain imaging during attention and ideation. Brain Research Bulletin. 50 (3), 149-165.

ROBERTS, R. M. AND TRAYNHAM, J. G. (1976). Molecular geometry: As Easy as blowing up balloons. Journal of Chemical Education. 53(4), 233-234.

RUSSELL, J. V. (1999). Using games to teach chemistry: An annotated bibliography.

Journal of Chemical Education. 76(4), 481-484.

SERAPHIM (1996). Project SERAPHIM: Clearinghouse for instructional computer information in chemistry. http://ice.chem.wisc.edu/seraphim/.

SALOMAN, G., PERKINS, D. N. & GLOBERSON, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. Educational Researcher, 20 (3), 2-9.

SANGER, M. J. AND BADGER, S. M. II (2001). Using computer-based visualization strategies to improve students' understanding of molecular polarity and miscibility. Journal of Chemical Eduacation. 78(10), 1412-1416.

SANGER, M. J., PHELPS, A. J. AND FIENHOLD, J. (2000). Using a computer animation to improve students' conceptual understanding of a can crushing demonstration. Journal of Chemical Education, 77, 1517-1520.

SHAW, C. A. AND MCEACHERN, J. C. (EDS.) (2001). Toward a theory of neuroplasticity. London: Psychology Press.

SHAW, D. E. (1998) Report to the president of the use of technology to strengthen K-12

education in the United States: Findings related to research and evaluation. Journal of Science Education and Technology, 7, 115-126.

SINEX, S. A. AND GAGE, B. A. (2003). Discovery learning in General Chemistry enhanced by dynamic and interactive computer visualization. The Chemical Educator. 8(4).

SMITH, S. G. AND CHABAY, R. (1977). Computer games in chemistry. Journal of Chemical Education. 54(11), 688-689.

STERR, A., ELBERT, T. AND ROCKSTROH, B. (2002). Functional reorganization of human cerebral cortex and its perceptual concomitants. In Fahle, M. and Poggio, T. (Eds.), Perceptual learning. Cambridge, MA: MIT Press.

TISSUE, B. M. (1996). Applying hypermedia to chemical education. Journal of Chemical Education, 73, 65-68.

TOWNS, M. H. AND GRANT, E. R. (1997). I believe I will actually go out of this class actually knowing something. Cooperative learning activities in physical chemistry. Journal of Research in Science Teaching. 34, 819-835.

TREADWAY, W. J. (1996). The multimedia chemistry laboratory: Perception and performance. Journal of Chemical Education, 73, 876-878.

TYSON, L, TREAGUST, D. F, AND BUCAT, R. B. (1999). The complexity of teaching and learning chemical equilibrium. Journal of Chemical Education. 76(4), 554-558.

WHISNANT, D. M. (2000). General chemistry multimedia problems. Journal of Chemical Education. 77(10), 1375-1376.

WHISNANT, D. M. AND MCCORMICK, J. A. (1997). Lake study for Windows update. Journal of Chemical Education Software. 5D1.

WILLIAMSON, V. M. AND ABRAHAM, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. Journal of Research in Science Teaching, 32, 521-534.

WINDSCHITL, M. AND ANDRE, T. (1998). Using computer simulations to enhance conceptual change: The roles of constructivist instruction and student epistemological beliefs. Journal of Research in Science Teaching, 35, 145-160.

WOODFIELD, B. F., ET AL. (in press). The Virtual ChemLab project: A realistic and sophisticated simulation of inorganic qualitative analysis. Journal of Chemical Education.

YALCINALP, S., GEBAN, O. AND OZKAN, I. (1995). Effectiveness of using computer-assisted supplementary instruction for teaching the mole concept. Journal of Research in Science Teaching, 32, 1083-1095.

ZARE, R. N. (2002). Visualizing Chemistry. Journal of Chemical Education. 79(11), 1290-1291.

ZIELINSKI, T. J. (2001). MathCad in the chemistry curriculum: Using symbolic software to facilitate learning. Journal of Chemical Education. 78(2), 270-271.