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Animations and Simulations for Teaching and Learning Molecular Chemistry

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This article explores past, current, and ongoing research associated with the evolution of design principles for effective animations for teaching and learning molecular sciences. Much of the data and background information in this paper results from the efforts of researchers working on a National Science Foundation sponsored project (REC-0440103) headed by Dr. Loretta Jones at the University of Northern Colorado. The project team's goal is to develop design principles related to the development of visualizations that insure adequate perception and comprehension in the applied context of student learning. Thus, their research simultaneously informs cognition science, educational technology, and chemistry education. Additionally, this research is helping people to develop and test innovative animations and visualizations for the science classroom. Animated visualizations that show both structures and processes help teachers convey important scientific concepts in chemistry and molecular biology. Designers of these animations benefit from knowing how students perceive and comprehend such visualizations.

Keywords: chemistry, cognitive load theory, computer animations, simulations, and design principles

INTRODUCTION

Animated visualizations that show both structures and processes help teachers convey important scientific concepts in chemistry and molecular biology. Designers of these animations benefit from knowing how students perceive and comprehend such visualizations. Specifically, instructional developers seek to design visualizations that allow students to learn critical concepts and relationships between these concepts. Students learn molecular chemistry concepts and relations by attending to, seeing, and understanding all the associated elements and the ways that they change and evolve during the process. Because often animations are too complex to be quickly understood, learners need to establish accurate mental models to assist in their comprehensions.

This article explores past, current, and ongoing research associated with the evolution of design principles for effective animations for teaching and learning molecular

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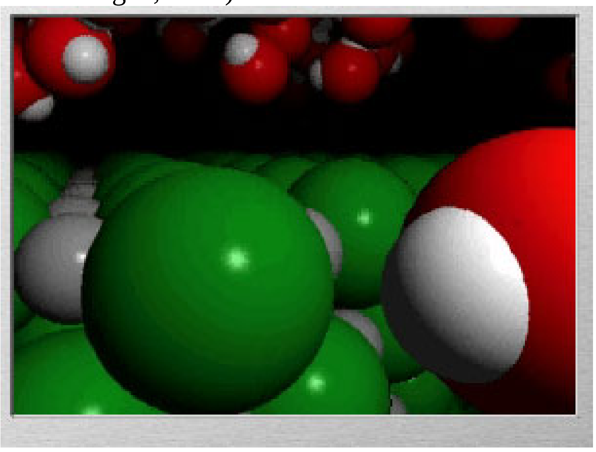
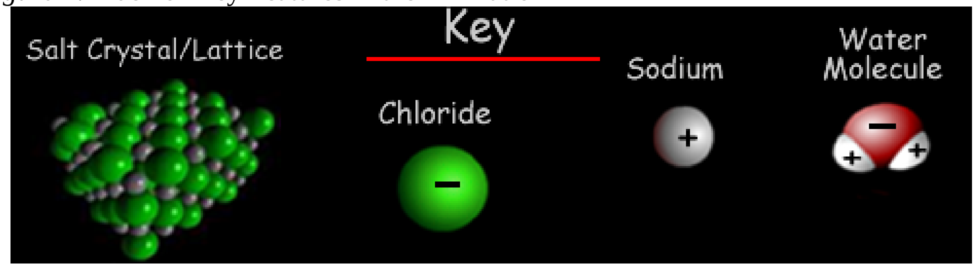
There are historical problems in the use of animations for teaching a wide range of topics (Tversky, 2003). Animations can mislead learning causing misunderstandings and misperceptions. Viewers often interpret movements of forms and figures in an animation as having causality, agency, and even intention (Martin & Tversky, 2003). Learners assume that the colors and the shapes reflect the actual reality of the represented items, when often the shapes and colors are either symbolic or an idealization of time and space relations. One example is described when students watch an animation of moving molecules (Tasker, Dalton, Sleet, Bucat, Chia, and Corrigan, 2002). The molecules are symbolized by tumbling balls of different colors coming apart and coming together. Students see these balls as pushing others so they will join or adhere (Tasker, 2004). However, studies by Sanger, Phelps, and Fienhold (2000), Burke, Greenbowe and Winschitl (1998), Sanger and Greenbowe (1997), and Williamson and Abraham (1995) have suggested that students who receive instruction including computer animations of chemical processes at the molecular level are better able to answer conceptual questions about particulate phenomena.

Figure 1. Image of Molecules from Salt Dissolving in Water Animation (Tasker, Dalton, Sleet, Bucat, Chia, and Corrigan, 2002).



In another recent study, researchers found that animations help students better understand dynamic molecular processes (Kelly & Jones, 2005). However, students take animation features literally and hence may misinterpret them, especially in cases where explanations are not clearly provided. Visualizations, when effectively designed and used help to insure adequate perception and comprehension in the real-world context of student learning (Tversky, 2001; Tasker, 2004). To be effective in teaching and learning, animations and interactive educational simulations must be designed based upon what is known about the principles of learning (Leahy & Sweller, 2004). Because studies show the potential positive effects of animations for learning and for developing mental representations, properly designed animations will provide instructors with new tools for teaching and learning science concepts.

Figure 2. Index of Key Features in the Animation



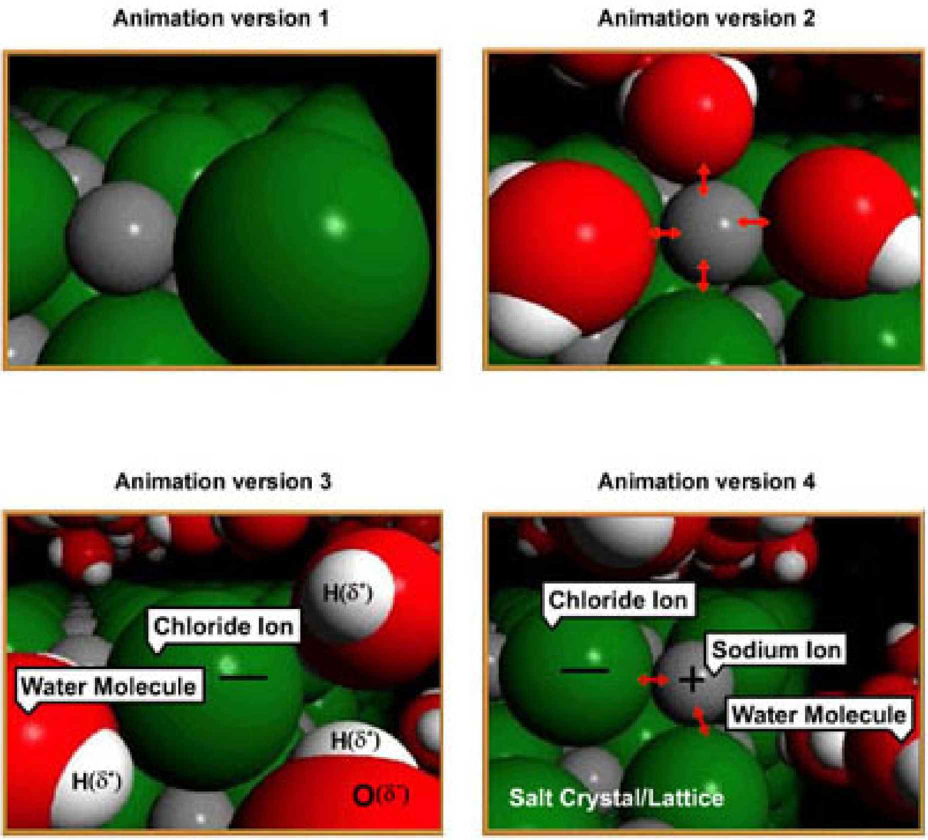
ANIMATIONS FOR CHEMICAL EDUCATION

Animations and simulations visually help students understand difficult concepts related to the dynamics of complex chemical systems including molecules and reactions (Kozma & Russell, 2005). However, exploring the dynamics of interactions among students and how students interact with the tools merits attention from research. Group discussions about previously viewed animations help students notice aspects of the animation that they might miss while viewing the animation (Kelley, 2005). However, student mental models are positively and negatively affected by viewing animations of basic chemical processes. Kelly suggests that because students often take molecular chemistry animations literally, explanations must be provided to address misrepresentations. These explanations can often be implemented as discussions among students with guidance from an instructional facilitator.

Much can be learned about teaching with animations through the eyes of chemists, educators, and cognitive psychologists (Jones, Jordan, & Stillings, 2005). Such collaborations lead to important research about integrating visualization in chemistry education. Helping students make connections between fragments of concept teaches students to problem solve and interact with content as opposed to memorizing rules or fragments of information (Suits, 2003). Combining animations with microcomputer-based laboratory experiments supports student integration of multiple representations of chemistry concepts (Suits, Kunze, & Diack, 2005). Clearly, many lab experiments are complemented by multimedia simulations and animations that represent the phenomenon being explored by students. Often, instructors help students use animations and technology to stay on task and to solve a complex scientific problem where guidance is provided as needed to sustain educational progress among the learners.

Laboratory instruction helps students understand the connections between their macroscopic observations of chemical phenomena and the underlying molecular processes. Visual representations help students develop multiple representations for the same chemical phenomenon during laboratory work. Molecular animations are an external representation that corresponds to the mental images that chemists use to solve authentic research problems. Microcomputer interfaced laboratory experiments provide students data from sensory probes (e.g., themistor or pH probes) while simultaneously displaying its graphical representation (e.g., time vs temperature or pH) in real time. When students connect their macroscopic observations of the phenomenon to the graphical representations they are truly learning chemistry and chemical processes.

Figure 3. Screen Shots of the Four Animation Versions Related to Arrows and Labels**.**



Because project-based science learning is a popular model for reforming the science curriculum technologies offer extensive opportunities for collaboration and cooperative learning (Harasim, 1990; Riel, 1990). Using the Internet, students can collaborate with other students as well as with scientists from around the world. Maor and Taylor (1995) conducted a teacher case study documenting a constructivist approach to teaching and learning using the Internet for science. In this classroom, students worked together to generate creative research questions for which they designed and conducted their own complex scientific investigations. Several research projects have more recently explored the use of integrated technologies for science learning. For example, *ChemSense* allows students to learn about chemistry and to build their own representations about what they are learning, while using authentic data (Stanford, Rosenquist, & Schank, 2002). In another example, Dr. Jerry Suits at the University of Northern Colorado developed the *Collaborative Chemistry Laboratory Model* to overcome difficulties students encounter in learning chemistry in the lecture hall and laboratory (Suits & Diack, 2002). In suits model students use three technologies to engage in scientific investigations of chemical phenomena. First, interfaced experiments allow real-time engagement at the macroscopic level and graphical representations on the computer display (Suits, Kunze, & Diack, 2005). Second, molecular animations display visually the corresponding molecular processes. Third, Students participate in online discussion forums to exchange ideas and further develop their own mental models. This model provides much promise for needed research about using animations and simulations for chemistry learning.

VIRTUAL LEARNERS

One study indicated that more K-12 students use their home computers for computer games than for school homework assignments (National Center for Educational Statistics, 2003). Clearly, computer and video animations are a part of the daily lives of students at the K-12 level (Simpson, 2005). These same students have expectations of their educational environment that include the nuances of the technical environment such as multimedia, and complex interactivity (Squire, Giovanetto, Devane & Shree, 2005).

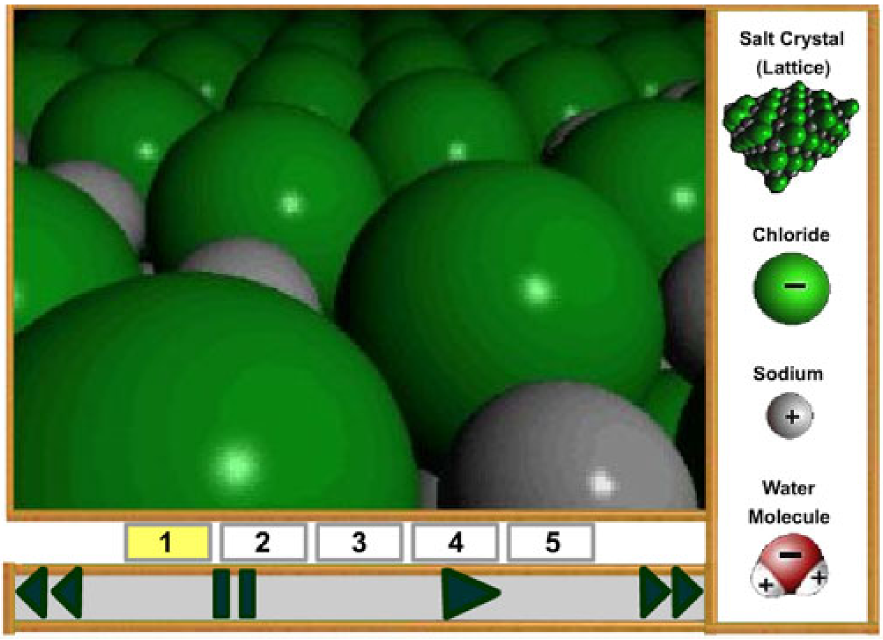
Much like computer games, educational simulations and animations engage students in virtual worlds where they apply their knowledge, skills, and thinking in virtual situations (Gredler, 2004). Because learning in general, as well as how people learn is multidimensional (Gardner, Kornhaber, & Wake, 1996), simulations and animations provide multi-sensory interaction, visualization, and symbols. Visualizations and symbols augment human cognitive capacities and help to convey concepts and information (Tversky, 2001). Much more effective than tutorials and drills, simulations enhance motivation, transfer of learning, efficiency, and flexibility while being safe, convenient, and controllable over real experiences (Alessi & Trollip, 2001). Today, children recreate playing video & computer games, watching MTV, Instant Messaging, and watching action movies (Simpson, 2005). Taking students out of these environments, in which they have become accustomed, may impact the motivation and attentiveness of these learners (Squire, Giovanetto, Devane, & Shree, 2005).

The rapid increase in popularity of computer-based gaming encourages educators to develop more interactive ways to engage their students. Responses from students are overwhelmingly positive when technology is introduced and used to help them learn (Prensky, 2001). Because gaming is becoming popular, many corporations and institutions are integrating gaming simulations into their training programs (Aldrich, 2004). Successful educational simulations merge the engagement power of games with instructional content, and, these games are fun but not frivolous (Prensky, 2005). According to Prensky (2001), The United States Military spends in excess of $2 billion a year on training. Much of the training provided to soldiers includes the use of technology and simulations for learning. These forms of training are used to teach skills that have a potential dangerous outcome (i.e. flying a stealth bomber, or navigating a naval destroyer). Although considered innovative, the use of games and simulations for military training dates back war games of the 1600s where armies and navies played war for training (Gredler, 2004).

INSTRUCTIONAL DESIGN ISSUES

Instructional design theory provides a foundation for developing animations and simulations that are effective learning solutions (Thomas, 2003; Reiser & Dempsey, 2002). Instructional design theory is the analysis of learning structures and the detailed development of instructional situations. The high-end expensive technology often used to produce the animations provides complex special effects and interactions. However, effective animations must reach specific outcomes related to skills or acquired knowledge for users. Researchers have long been interested in how to best structure virtual learning environments (Mayer, 2003; Sweller, 1999).

Figure 4. Screenshot of the interface design of the animation including controls.



Much like good maps, quality animations can illustrate structure and spatial elements and relationships. Tversky (2003) concludes that maps don't necessarily have to be spatially accurate to work effectively in teaching such relationships. Effective graphics and maps are never representative (one-to-one) and usually expand or compress time and distances. Effective animations might also distort perspectives and space to illustrate important features and concepts. Additionally like many map and diagram designers do, animation developers might include pictorial devises such as symbols, arrows, boxes, and brackets. Often these devices can help learners focus on important features and processes in the animation, signaling learners about important features in these complex animations.

Foundational instructional design research conducted by Pavio (1986) clearly indicated that picture and graphics teach better than written or aural words. Additionally, simple pictures are as effective as complex, detailed pictures. More interesting for animation designers, Pavio found that teaching with pictures combined with words increased memory-recall and transfer of information. More recently, Mayer (2001) has developed a research-based cognitive theory of multimedia learning, which is founded in the earlier work by Pavio and other researchers. Mayer conducted many studies of animations and diagrams that concluded duel channels for cognitively processing information. For example, when we see and hear something at the same time our mind coordinates both of these separate channels. This is the case with all of our senses, but it is much more prevalent with vision and hearing. Mayer found that word and pictures should be used simultaneously and should be presented close to each other in space. Additionally, Mayer found that audio narration is superior to textual explanations. These design principles have much more impact upon novice learners whom have higher spatial perceptions and abilities. Because the body of research has been well developed, it behooves animators to follow Mayer's guidelines.

Mayer (1998) also defines learning processes as selecting, organizing, and integrating, which occur throughout the phases of memory development. He suggests that short-term memory serves as a mediator between the stimuli and cognition, and that there are limitations in the capacity of working memory. There is a relationship between long- and short-term (working) memory in that information passes through short-term memory before becoming long-term memory (Sweller, 2004). Sweller's cognitive load theory suggests that short-term (working) memory has a limited capacity and can be overloaded. Because many animations are conveying a variety of structural and functional issues, these complex animations will overload working memory quite quickly.

Because students with prior knowledge are more successful using animations for learning (Mayer, 2001), instructors provide scaffolds from prior knowledge to new information (Suits, 2000). One such way to activate and use prior knowledge is to have students make predictions about what happens next during the use of animations for learning. Hegarty, Kriz, and Cate (2003) found that combining predictions with animations was more effective than animations alone when learning about a mechanical system. Additionally, the use of predictions with animations increases the interactivity of the animation during the learning process.

Much like many other educational technology tools, animations need to be integrated into a larger learning environment (Tasker, 2004). Instructors focus attention on students' prior knowledge while drawing students' attention to key features and functions portrayed in the animation. Because students learn better when they control the pace of the instruction (Mayer & Chandler, 2001), effective animations are segmented and offer features such as pause and replay buttons. Additionally, increasing the level of interactivity of animations stimulates engagement and motivation of learners (Lowe, 2004).

USABILITY OF ANIMATIONS

Designers of animations explore the user's (learner's) perspectives, developing the interface and design to address the needs of the user. Defined as the instructional cues between a system and a user, an interface is the form and function of connecting to the instructional system (Hackos & Redish, 1998; Marchionini, 1995; Lohr, Falvo, Hunt, & Johnson, 2006). As apposed to a system-centered design approach (Johnson, 1998), usability design addresses the needs and situations related to the end-user of the technical piece, the animation. User-centered theory speaks to the user's perceptions and the user's situation. Aesthetics and attractiveness impacts student attitudes towards using an animation (Lidwell, Holden, & Butler, 2003). When learners find the interface to be attractive and aesthetic, they tend to perceive the system as being effective. Addressing these perceptions helps learners find animations as easier to use, as more readily accepted, and as a motivation for problem solving.

SUMMARY

In summary, animations assist students to better understand dynamic molecular processes in chemistry and biochemistry. However, students often take animation features literally and hence misinterpret the concepts presented in the animation. Additionally, students attempt to explain what they see by using their prior knowledge, which may be flawed or applied inappropriately. Instructional use of animations and visualizations must be accompanied by pre- and post-explanations and discussions to address misrepresentations. Solid foundational (prior) knowledge prepares students to learn and retain structural and process concepts conveyed by animations.

Because there have been recent advances in technology and availability of equipment, the possibilities for educational animations and simulations are endless. These educational tools can range from simple, single user simulations to multi-user interfaces that are complete virtual simulations. Much more research is needed to determine how to best structure and use these innovative tools. Because there are wide ranges of types, uses, and structures of animations and simulations for learning, generalizing findings can be a daunting challenge. Because development tools are readily available and much easier to use today, the trend of teachers designing and implementing their own animations will continue. As this trend of easy development is combined with broader understanding of how such tools can help teaching and learning, the use of animations and simulations in classrooms will likely grow. If these tools are to live up to their promises to improve teaching and learning in science, researchers must continue to address how to best design and integrate these complex tools into our modern science classrooms.

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