Choosing effective multimedia simulations for chemistry learning: What *Molecules & Minds* research shows

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Abstract:

*Molecules & Minds* is in its 8th year researching how to improve the effectiveness of simulations based on kinetic molecular theory. Our immediate goal is to help learners explore and understand observable, symbolic, and explanatory levels of representation through interactive multimedia resources that allow learners to control variables and pacing. Our key findings: big ideas need a simple design; icons work better than symbols; freedom to explore supports learning and engagement; problematizing narratives that bring science from the classroom into the everyday world lead to better learning outcomes; and that topic order may be important for learning, are presented.

Introduction

The aim of the *Molecules & Minds* project was to develop and evaluate high-impact, theory based chemistry simulations optimized for a broad range of learners, including students from racial and ethnic minority groups that have underachieved academically. Our simulations were designed and developed around different chemistry topics associated with kinetic molecular theory of diffusion, gas laws, and phase change. Each simulation begins with a narrative to introduce everyday phenomena that require a model in order to be explained. The ultimate goal was to use these simulations to supplement the teaching and learning of chemistry in high school.

Simulations provide a model in which participants can manipulate variables and generate graphs that communicate the relationships between variables, an important process in developing understanding in science. Research shows that simulations produce better learning than static pictures (Höffler & Leutner, 2007).

The *Molecules & Minds* project began with the development of the simulations, based on theories of learning, research in cognition, and best practices in science education. Experiments were carried out in both urban and rural classroom setting across the country to investigate the effectiveness of different types of visual representation and instructional format. Usability and efficacy studies contributed to the refinement of the simulations, which were evaluated based on posttests that evaluated knowledge and transfer.
Figure 1: Still picture of the Gas Laws simulation. In this scenario, the learner has locked pressure at 5.5 atm, and may manipulate volume and temperature by clicking and dragging the sliders. The data points are automatically plotted on the graph on the right.

Our studies indicated that the simulations fostered student learning of chemistry concepts (e.g., Homer & Plass, 2009; Homer, Plass, Milne, & Jordan, 2009; Plass et al., 2012). However, in the process of designing, developing, and testing these simulations we became increasingly aware of the need to provide additional support for the learners who used them. Even though our simulations helped learners with little prior experience of the particulate level of representation, some learners still needed further instructional support to be able to move between different levels of representation. In particular, understanding the relationship between different levels of representation (observable, explanatory, and symbolic) and being able to move between these levels in order to explain and communicate these understandings remains a challenge for all learners and a focus of our study.
Theoretical Framework:

The theoretical framework for the design of the Molecules & Minds simulations is based on five principles:

- **Learning is Active** (e.g., Bonwell & Eison, 1991): Our simulations are designed to involve learners in defining a problem, making predictions and experimenting, forming hypotheses, and observing and interpreting data from various sources, including the data they generate with the simulation. The simulations have been tested with learners who showed us that they preferred to be actively involved in learning.

- **Context is Everything** (e.g., Brown, Collins, & Duguid, 2008): We use stories/narratives in our simulations to bring the everyday to science and science to the everyday. Our goal is to help learners realize that we can use science to explain phenomena we experience in our daily lives.

- **Learners Can Learn More with Scaffolding** (e.g., Vygotsky, 1978; Wood, Bruner, & Ross, 1976): Our scaffolding consists of two types; narrative and visual. We use narrative scaffolds to support learners in making connections between everyday experiences (e.g., smelling fresh popcorn) and the scientific explanations for these experiences (e.g., how particles diffuse). We use visual scaffolds to support learners in making connections between explanatory models and graphical representations (e.g., a representation of moving particles and a graph of data collected about those particles). Visual scaffolds can also support learners as they begin to use causal and probabilistic reasoning.
Visualizations Can Support Learning and Inquiry (e.g., Reigeluth & Schwartz, 1989): The idea that all forms of matter, solids, liquids, and gases, are made up of moving particles is critical to understanding Kinetic Molecular Theory. However, it can be difficult to imagine how these particles are behaving when we cannot see them. Using multimedia gives us the ability to represent these particles as well as their dynamic movement, and for learners to develop their own visual repertoire of particle behaviors. Utilizing interactive computer simulations further allow learners to engage actively in exploring the properties and behavior of these particles. In our simulations we work to provide opportunities for users to work on the connections between 1) experiencing everyday phenomena, 2) understanding these phenomena in terms of kinetic molecular theory, and 3) using words and images to communicate these connections. In chemistry education this is called levels of representation.

Model-Based Inquiry (e.g., Windschitl, Thompson, & Braaten, 2008): We use model-based inquiry to foster thinking within levels of representation. Our simulations rely heavily on student interaction with the simulation environment to allow learners to generate predictions based on their own manipulations and observations.

What Our Research Shows:

1. What should the resource look like?

   *Big ideas need a simple design*

   Bombarding the learner with unnecessary information inhibits learning (e.g., Brunken, Plass, & Leutner, 2003; Plass, Moreno, & Brünken, 2010; Plass et al., 2012; Sweller, 1988). Multimedia allows us to reveal the dynamic nature of matter. Through multimedia we can show particles in motion, with the goal of helping learners visualize the particulate nature of all matter. A previous study with middle school chemistry students found that those students in a low visual complexity condition scored better on posttest measures of comprehension and transfer than did students in a high visual complexity condition (Lee, Plass, & Homer, 2006). Several of our studies (e.g., Homer & Plass, 2009; Homer et al., 2009; Plass, Homer, & Milne, 2009; Plass et al., 2012) confirm that reducing extraneous cognitive load in chemistry simulations for high school learners produces better outcomes.

   When you look for resources, consider the importance of “clear and uncluttered”
2. How should the information be represented?

*Icons work better than symbols*

Icons have culturally accepted meanings. Words are complex symbols that must be decoded. Our research (Homer & Plass, 2009; Homer et al., 2009; Plass et al., 2009; Plass, Homer, & Hayward, 2009) found that high school learners in the iconic condition had better learning outcomes that those in the symbolic condition. Furthermore, the effect was strongest for those learners with low prior knowledge.

*When you look for resources, consider iconic representation*

![Figure 3: Gas Laws simulation with iconic representation](image3)

![Figure 4: Gas Laws simulation with symbolic representation](image4)
3. What learning strategies work best?
   *Freedom to explore supports learning and engagement*

   All learners value the opportunity to explore in a safe environment, even if they are not aware of it. We created two versions of the Gas Laws simulation: the *worked-out* condition presented learners with step-by-step procedures for hypothesis testing; the *exploratory* condition presented learners with some direction and structure, but required them to generate and test their own hypotheses (Homer et al., 2009). The exploratory condition produced better outcomes (recall and transfer), and produced greater motivation, as measured by time-on-task and click-counts.

   *When you look for resources, consider exploratory learning*

4. How is the material contextualized?
   *A problematizing narrative leads to better learning outcomes.*

   Problematizing narratives create a motivation to learn and help expand science learning from the classroom/lab into the outside world. Each simulation begins with a narrative that follows the pattern humans use to organize events: the narrative (a) presents a familiar phenomenon (e.g., a basketball that goes flat because it was left outside in the cold night air); (b) contains a clear beginning, middle, and end; (c) presents an agent who acts with intention; and (d) demands an interaction between the author and the reader (Bruner, 1991).

   Our efficacy studies found that using narrative to help explain observable phenomena, to help bring scientific concepts out of the classroom and into the world of the learner, and to get learners to think about what they know and what they don’t know did in fact promote student achievement with the simulations (Milne et al., 2010).

   *When you look for resources, consider a problematizing narrative that connects science concepts with students’ real-life experience.*
Figure 5: Problematizing narrative to introduce the Gas Laws simulation
5. What sequence of topics makes sense?

The order of topics may be important for learning

Learning complex theories will be more effective if the learner understands the underpinning concepts. We ran effectiveness studies (Plass et al., 2012) with more than 700 students in rural and urban high schools. Our results supported the effectiveness of the sequence of the simulations.

When you look for resources, consider whether the order of topics make sense

Conclusion:

We have briefly highlighted some of the research-based design features we have incorporated in our simulations to improve educational outcomes. We believe raising awareness about this research and these design features can be immensely valuable when it comes to selecting resources and optimizing outcomes. In addition, our research demonstrates the importance of one more variable: implementation (Plass et al., 2012).

Using simulations “seems to be a natural fit with good science teaching practice, offering opportunities for active learning, contextualized instruction, and the use of visualizations to clarify difficult concepts” (Plass et al., 2012, pp. 1-2). There is great hope that computer-based instruction can help increase motivation and lead to improved learning in science. We believe these research-based guidelines can help achieve those objectives.

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