The Effect of Adding Relevant and Irrelevant Visual Images to an Animation of an Oxidation-Reduction Reaction on Students' Conceptual Understanding

by

Martin H. Cole

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Mathematics and Science Education, Chemical Education Concentration

Middle Tennessee State University
2020

Dissertation Committee:

Dr. Michael J. Sanger, Chair

Dr. Dana Fuller

Dr. William Ilsley

Dr. Preston MacDougall

Dr. Amy J. Phelps

This dissertation is dedicated to my wife and family. Especially my wife, Maxcine, who has tirelessly supported my educational endeavor.

ACKNOWLEGMENTS

I would like to acknowledge and thank the efforts of my committee members, Dr. Dana Fuller, Dr. William Ilsley, Dr. Preston MacDougall, and Dr. Amy Phelps in helping me direct my research and critiquing my writing so this study could be brought to a fitting defense and conclusion. I especially want to recognize and thank Dr. Michael Sanger for his unwavering support during this endeavor. Dr. Sanger, thank you for your moral support, knowledge, help, guidance, and time during this long process of working towards the completion of this dissertation.

ABSTRACT

This dissertation is comprised of two research studies that examine how different visual images in animations of the oxidation-reduction reaction of copper metal and silver nitrate affect general chemistry students' explanations of the oxidation-reduction process. Each study compared students' explanations after viewing the chemical demonstration and one particulate-level animation. The first study presented in Chapter 2 consists of two experiments; the first one used two animations created by different researchers while the second one (the water molecules study) used two animations that differed only by whether water molecules were shown or omitted from the animation. In the first experiment, students viewing the more simplified animation provided better explanations of the process than students viewing the more complex animation for all concepts compared. For the second experiment, however, most students' explanations were not significantly different after viewing these two animations except that students viewing the animation with water molecules omitted were better able to identify nitrate ions in the animation. Additionally, students identified the animation with water molecules omitted as providing a clearer picture of the oxidation-reduction process. The two studies presented in Chapter 2 together suggest that showing or omitting water molecules in the animations had a limited effect on students' explanations of the oxidation-reduction process. The study presented in Chapter 3 investigates how changing the visual images associated with ion charges and transferred electrons in an animation affects students' explanations of the oxidation-reduction reaction. Students viewed one of four different particulate-level computer animations that differed in the way the ionic charges were depicted and the way the transferred electrons were depicted. This study showed that labeling the ion charges and depicting the transferred electrons as particles provided students with visually relevant information that enabled them to better explain some of the processes in the oxidation-reduction reaction and write a more correct balanced chemical equation than those students who viewed the animations omitting ion charges and depicting transferred electrons as halos around the metal atoms. Both studies demonstrate that showing relevant information in an animation of an oxidation-reduction reaction process had a significant impact on student's explanations of the oxidation-reduction process.

TABLE OF CONTENTS

Page

Page

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF ABBREVIATIONS

ANCOVA ……. Analysis of Covariance

ANOVA ……… Analysis of Variance

APM ………The animation processing model

MC ………… The more complex animation, created by Roy Tasker

MS ……………. The more simplified animation, created by Michael J. Sanger

NC_EH ……….. The animation with no ion charges depicted and depicting transferred electrons as halos

NC_EP ……… The animation with no ion charges depicted and depicting transferred electrons as particles

PNM ………….. Particulate Nature of Matter

Redox ………… Oxidation-Reduction

WC_EH ………..The animation with ion charges depicted and depicting transferred electrons as halos

WC_EP ………. The animation with ion charges depicted and depicting transferred electrons as particles

WO ……………. The animation with water molecules omitted

WS …………….. The animation with water molecules shown

LIST OF SYMBOLS

χ^2 ……………… The chi-square distribution

df ……………... Degrees of freedom

e^- ……………… Electron

F ……………… *F* distribution

ΔG ……………. Gibb's Free Energy

g ……………. Hedges' measure of effect size

p ……………… Probability

t ………………. Student's *t* distribution

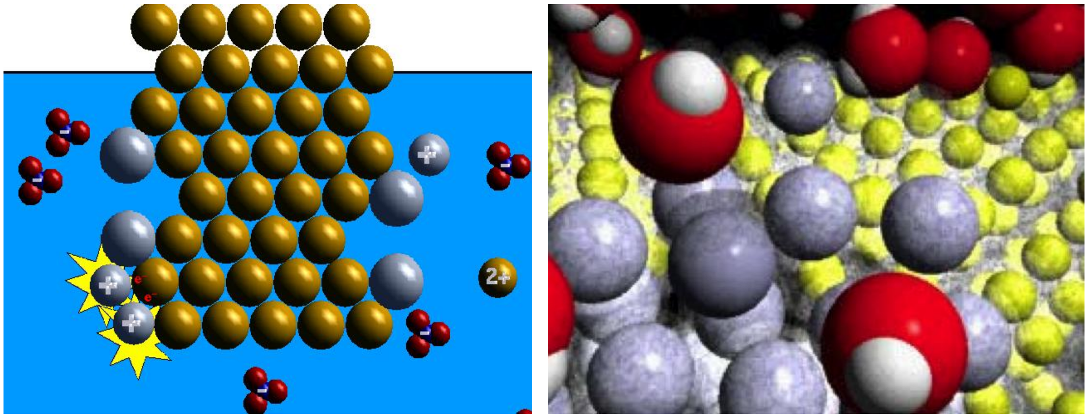
z ………………. A standardized score

CHAPTER 1: INTRODUCTION

In recent years, the use of animations in the chemistry classroom and in chemical education research studies has increased dramatically (Suits & Sanger, 2013). This increase is a result of the belief on the part of many educators that animations have the potential to benefit student learning and information processing (Lowe, 2004). However, Lowe (2016) pointed out that there is a competition between the learning benefits of the animation and the information processing costs that the animation places on the learner. Therefore, animations design needs to be addressed in order to reduce or minimize the information processing costs of an animation and increase its learning benefits. The research described in this dissertation examines animation design in order to help identify the critical components of animations that could improve student understanding of the chemical processes occurring in oxidation-reduction reactions.

Introduction to the Two Research Studies

The impetus for the research presented in this dissertation are some unanswered questions identified from the results of several chemical education research studies done by Rosenthal and Sanger (Cole, Rosenthal & Sanger, 2019; Rosenthal & Sanger, 2012, 2013a, 2013b). These researchers performed several research studies using computer animations of the same chemical reaction with different levels of complexity that were developed by two different researchers to determine which animation would be better at improving students' explanations of the aqueous silver nitrate – copper metal oxidation-reduction reaction. Figure 1 shows screen shots of the two computer-generated animations used in the Rosenthal and Sanger studies.



(a) (b)

Figure 1. Screen shots of the two animations used in the Rosenthal and Sanger studies. The simple animation (a) was created by Sanger and the more complex animation (b) was created by Tasker. Adapted from "Student Misinterpretations and Misconceptions Based on Their Explanations of Two Computer Animations of Varying Complexity Depicting the Same Oxidation-Reduction Reaction," by D. P. Rosenthal & M. J. Sanger, 2012, *Chemistry Education Research and Practice*, *13*, p. 474.

Rosenthal and Sanger's research (Cole, Rosenthal, & Sanger, 2019) found that the more simplified animation (Figure 1a) helped students provide better explanations of the oxidation-reduction process than the more complex animation (Figure 1b). The two animations differed in showing or omitting water molecules, the color changes of the aqueous solution as the reaction occurs, the charges of the ions in solution, the relative ratios of the silver and nitrate in solution, changes in the camera angle, depicting the oxidation-reduction process as an event that occurs at the same place and time or showing it happening in different places and at different times, showing the electrons as particles or as a sphere of "fuzziness", the reacting ratio of silver ions and copper atoms, etc. Because of these differences, Rosenthal and Sanger could not determine which ones were responsible for the differences in students' abilities to explain the oxidation-reduction reaction and which of these differences were largely irrelevant.

The goal of the research studies performed by me in this dissertation is to determine how the way three key features (water molecules, ion charges, and transferred electrons) of this reaction were visually depicted affected students' explanations of the oxidation-reduction process. To answer these questions, I performed two research studies that used modified versions of the more simplified animation in the Rosenthal and Sanger's studies (Figure 1a) that only differed from each other in the way that these three key features were visually depicted in the animations. For my first research study (Chapter 2), the more simplified animation was used as before and a similar animation was created that depicted water molecules in aqueous solution; for my second research study (Chapter 3), the more simplified animation was modified to create four animations that either showed or omitted ion charges and that depicted the transferred electrons as discrete particles or as an electron "halo" representing valence electrons on an atom.

The studies in these papers used a mixed methods design approach known as a Concurrent Nested Strategy (Creswell, 2003). A Concurrent Nested Strategy allows for qualitative and quantitative data to be collected simultaneously. Within these studies, the collection of quantitative data is embedded in the collection of qualitative data (Creswell, 2003). The theoretical framework and methods used in collecting and analyzing the data for each of these studies are discussed in more detail in Chapters 2 and 3.

In the literature review that follows, the foundational research and the theoretical frameworks for Chapters 2 and 3 of this dissertation are discussed.

Literature Review

Johnstone's review (1993) of the evolution of teaching chemistry described the dramatic changes that have occurred in the chemistry classroom since the middle 1700's. As the need for chemical technicians and chemists grew during the industrial revolution, chemistry teaching moved from an apprenticeship model to a lecture/laboratory model. The introduction of chemistry as a subject in high schools began in the 1800's. Its acceptance was slow and it was not until the 20th century that chemistry instruction became available for the masses (Johnstone, 1993). After multiple decades of teaching chemistry the way it had been taught (teachers instructing as they were instructed; in many cases, using the exact same notes as their predecessors), in the 1960's a new curricula began to emerge with an updated content that focused on general principles instead of individual reactions and individual inquiry instead of demonstrations. This updated content was designed, not only to provide background and theory to the subject, but also to make chemistry a coherent, understandable, intellectually stimulating subject (Cooper & Klymkowsky, 2013). Unfortunately, these new approaches to teaching chemistry led to a decline in student interest in chemistry as evidenced by the declining number of students enrolling in university and college chemistry courses. As a result of the failure of this new curricula to develop students' interest in chemistry, some chemistry educators shifted their focus from how chemistry is taught to how students learn chemistry (Johnstone, 1993).

Through the application of general learning theories to the chemistry classroom, an evolving paradigm of the way students learn chemistry was developed. Chemistry education researchers (Bodner, 1986; Bunce, 2001; Herron, 1975; Nurrenbern, 2001) started applying the theory of constructivism to how students learn chemistry. Constructivism posits that learners construct his or her own understanding based on the intake of new information and its connection to their prior knowledge and experiences. Constructivism has as its foundation the cognitive development work of Piaget (Inhelder & Piaget, 1958), Von Glaserfeld (1980), and Ausubel (1978).

Piaget believed knowledge is built through a life-long construction process that organized, structured, and restructured incoming information through existing knowledge (also called prior knowledge or schemes of thought). Throughout this process, the learners' schemes of thought are modified and expanded (Bodner, 1986). Von Glasersfeld (1980) believed that learners' experiences test the usefulness of his or her knowledge and that knowledge is only useful if it works and fits the parameters of their experiences. That is, learners' must align his or her new knowledge with his or her prior knowledge so that the new knowledge makes sense to them. Ausubel (1978) believed that meaningful learning was a result of learners relating new knowledge to his or her prior knowledge. Thus, prior knowledge is perhaps the most important factor influencing learning (Bodner, 1986).

From an information-processing perspective, prior knowledge is stored in the brain in a learner's long-term memory (Johnstone, 2010) through the development of mental networks. The work of Piaget, von Glasersfeld, and Ausubel also acknowledged the importance of students developing correct mental networks. These mental networks are described by Chi (1992) as *ontological categories*, which are distinct conceptions of the world. Matter, events, and abstractions are a few examples of these distinct conceptions. Ontological categories are also termed *schemata* (or using the singular form of the word, *schema*) (Chi, Glaser, & Rees, 1982; Piaget & Cook, 1952) or *mini-theories* (Claxton, 1990). Schemata have been described in variety of ways. Piaget and Cook (1952) suggested that schemata represented a method of organizing knowledge and the building blocks of intelligence while Chi, Glaser, and Rees (1982) thought of them as highly-ordered categories of long-term memory. Others have described schemata as "mental framework[s] for understanding and remembering information" (Kirschner, Kirschner, & Paas, 2008, p. 205) or "a cognitive construct that organizes information according to the manner in which it will be dealt" (Sweller & Chandler, 1994, p. 186), which fits nicely with Wadsworth's (2004) understanding of schemata as a filing system of index cards in the brain that allow the learner to react to incoming information. Unfortunately, the information in the learner's long-term memory may be organized or filed incorrectly, which leads to misinterpretations and misconceptions of the subject matter.

Misconceptions. Constructivism recognizes that a learner can take in information, process it, and construct knowledge lacking vital aspects required for complete understanding of a concept. This incomplete or partial knowledge constructed by the learner has been referred to as *misconceptions*, *naïve ideas*, or *alternate conceptions* (Mulford & Robinson, 2002; Sanger & Greenbowe, 1997a ; Treagust, Chandrasegaran, Zain, Ong, Karpudewan, & Halim, 2011). Chi and Roscoe (2002) viewed misconceptions as *mischaracterizations* or the incorrect manipulations of incoming information. Based on the understanding that concepts as they are received by a learner are categorized, Chi and Roscoe believed misconceptions involved the assignment of a concept to the wrong schema – in other words, the misplacement of an index card in the filing system in the brain.

Misconceptions about science topics can also be explained by the idea that the understanding of scientific concepts belongs to a different schema than the intuitive understanding of naive ideas about science. For example, Chi (1992) suggested that students tend to place science concepts into the schema of material substance, where they use the behavior and properties of matter to explain all the behavior and physical properties of science concepts. However, many scientific concepts (e.g. heat, light and current) are abstract and need to be explained in ways other than through the application of the properties and behavior of matter. Understanding these types of abstract concepts requires students to develop a different schema of a *constraint-based event* (Chi, 1992). Constraint-based events "exist only as defined by relational constraints among several entities, and their existence depends on the values or status of these other variables." (p. 141). An example of a constraint-based event is electric current, which only occurs when charges move in an electric field between two points. Novice learners often have difficulty developing this new kind of schema and making changes from the material substance schema to the constraint-based event schema (Chi, 1992).

Many chemistry misconceptions may also develop because students have difficulty placing these concepts into a mental category consisting of constraint-based events. Misconceptions are prevalent among students and their existence has been well documented in many areas of chemistry such as chemical reactions, the dissolution of compounds in water, writing balanced chemical equations, oxidation-reduction reactions, chemical bonding, and electrochemistry (Boo, 1998; Ebenezer & Erickson, 1996; Garnett & Treagust, 1992a; Kelly & Jones, 2008; Naah & Sanger, 2012; Österlund, Berg, & Ekborg, 2010; Özkaya, 2002; Rosenthal &Sanger, 2012; Sanger, 2005; Sanger & Greenbowe, 1997a; Smith & Nakhleh, 2011; Yarroch, 1985). As an example, some students in the Rosenthal and Sanger (2012) study had the misconception that the blue sphere (nitrogen atom) in the blue-red cluster representing the nitrate ion in a computer-generated animation represented the blue color in the aqueous solution. These students did not realize that the change in color of the solution occurs because the blue hydrated copper (II) ions were produced during the reaction. Instead, the students related the change in color of the solution to the scientifically accepted (but completely arbitrary) use of a blue sphere for the nitrogen atom in the nitrate ion, which was not involved in the reaction at all. Not only is it important to understand where these misconceptions come from, it is also important to understand why they happen – why do learners have difficulty developing correct chemistry schema, which ultimately makes the learning of chemistry a difficult task for many students?

Why is chemistry difficult? Many researchers have studied the difficulty students face when learning various topics in chemistry such as the mole concept, atomic structure, kinetic theory, thermodynamics, chemical change and reactivity, stereochemistry, chemical bonding, solution chemistry, intermolecular forces, and (pertinent to this dissertation) oxidation-reduction reactions and electrochemistry (Sirhan, 2007). Within the overall topic of misconceptions in oxidation-reduction reactions and electrochemistry (which is the focus of this dissertation), misunderstandings and difficulties exist at many different levels: galvanic and electrolytic cells (Garnett & Treagust, 1992b; Loh & Subramaniam, 2018; Sanger & Greenbowe, 1997a; Schmidt, Marohn, & Harrison, 2007; Supasorn, 2015; Tsaparlis, 2018), oxidation-reduction reactions (Brandriet & Bretz, 2014b; De Jong, Acampo, & Verdonk, 1995; Garnett & Treagust, 1992a; Lu, Bi, & Lui, 2018, 2019; Rosenthal & Sanger, 2012), and the electrical conductivity of aqueous solutions (Lu & Bi, 2016; Lu, Bi, & Lui 2019; Nyachwaya, 2016; Sanger & Greenbowe, 1997b). Why do these topics prove difficult for students? Sirhan (2007) and Suits (2015) posit that it is because of chemistry's highly conceptual nature and students' propensity to fragment and memorize instead of trying to connect the fragments into a complete picture of the topic. Another reason chemistry students tend to have difficulty characterizing chemical concepts is the presentation of these topics in textbooks. Gabel (1999) asserted that a quick look at introductory chemistry textbooks showed that textbook presentations often occurred on the abstract level rather than at a level that novice chemistry learners could understand. In-depth studies of college chemistry texts' presentations of electrochemistry and oxidation-reduction found that some misconceptions developed from unclear or misleading language in the text or known misconceptions that were not addressed at all. Österlund, Berg, & Ekborg (2010) noted that an inconsistency among introductory, organic, and biochemistry textbooks in describing the oxidation-reduction process led to student confusion, which became a factor in the development of student misconceptions.

Even when misconceptions were addressed in the textbook, Sanger and Greenbowe (1999) found that students still developed misconceptions. So what else contributes to the construction of misconceptions of chemical concepts?

Prior knowledge has also been linked to the development of misconceptions. As students learn, they construct new or revised understandings based on their interpretation of the new information and how it aligns with their existing knowledge. This new information can reinforce a misconception if the misconception allows the student to make sense of what they have observed (Appleton, 1989, 1993; Mulford & Robinson, 2002). Notice what Treagust, et al. (2011) said about the problems caused by prior knowledge:

> These intuitive ideas about the nature of matter that students have acquired in their early years of schooling appear to change to scientifically acceptable understandings only to a limited extent after instruction. It appears that students' naïve ideas tend to be deeply engrained in their cognitive structures and hence become resistant to change. The resistance to change of students' conceptions is not unexpected as these conceptions are deep-rooted and often "*difficult to shift, and can offer a serious barrier to effective teaching*" (p. 252). [Emphasis appears in original text]

This quote offers insight into the challenge chemistry educators face when attempting to help chemistry students construct the scientifically accepted understanding of a topic. Johnstone (2006) provided another reason as to why students have difficulty with chemistry topics, which is discussed in more detail later in this chapter – the limited capacity of the working memory.

A learning model for chemistry. In order to understand how the deep-rooted and hard to change misconceptions of chemistry concepts can be, it might be useful to examine a model of the way chemistry students form, retain, or change their understanding of chemistry concepts. Such a model was developed by Appleton (1989) and is shown in Figure 2.

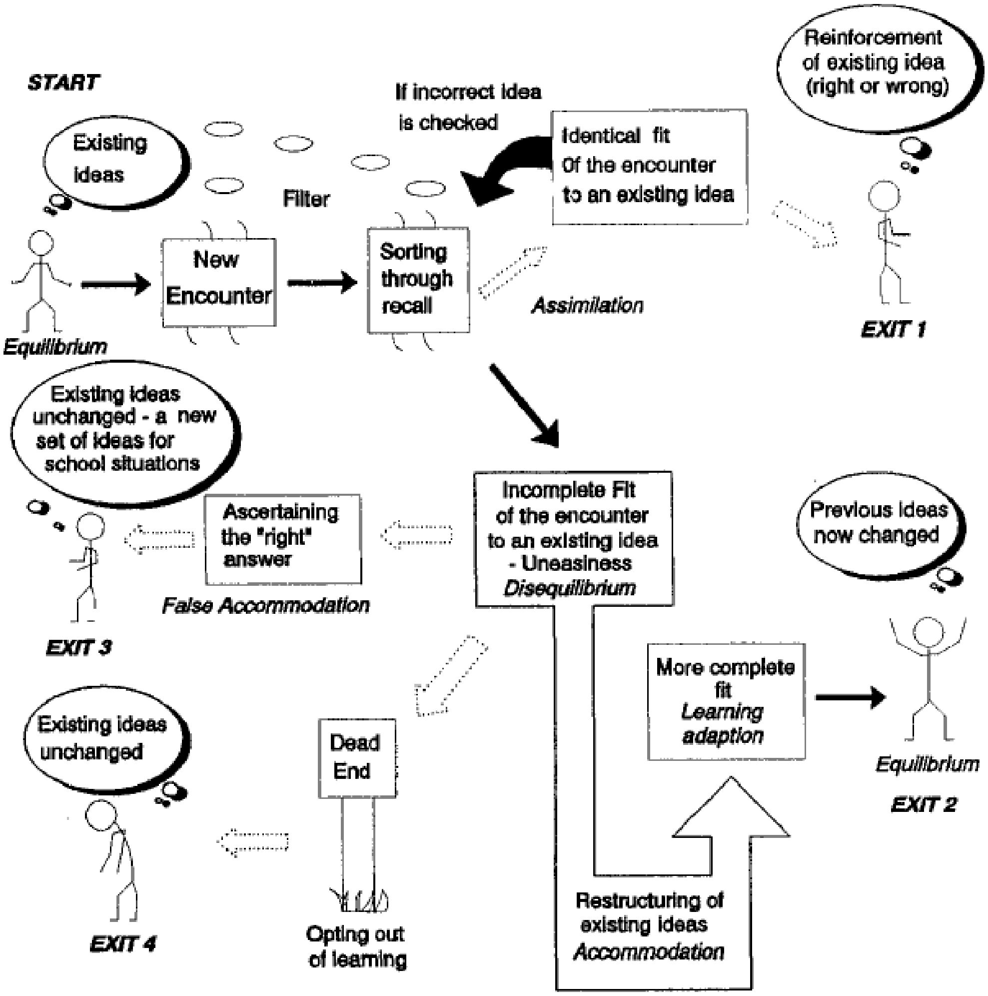


Figure 2. A learning model for science education. Reprinted from “Using Theory to Guide Practice: Teaching from a Constructivists Perspective” by K. Appleton, 1993, *School Science and Mathematics, 93*, p. 270, and used with permission (see Appendix D)

In the development of his model, Appleton used the ideas of assimilation, disequilibrium and accommodation from Piaget in combination with the concepts of how misconceptions occur.

A common misconception among secondary chemistry students is that water decomposes into hydrogen and oxygen when it is boiled (Mayer, 2010). It is difficult to determine whether this misconception is a result of the student's prior knowledge before entering chemistry or if it was developed when the student was asked about boiling water in class. Regardless of when this alternate concept was devised, the student enters the learning environment in equilibrium, comfortable with his or her understanding of what is happening when water boils (Appleton, 1989, 1993). In class, the student observed the following demonstration. Hydrogen was shown to be flammable; oxygen was not flammable, but supported combustion; and water vapor was not flammable. The gaseous product of boiling water was collected in a balloon and an attempt was made to ignite the vapor. Students saw that product did not catch fire and in fact it extinguished the flame (Mayer, 2010).

According to the learning model presented in Figure 2, a student enters the learning environment with his or her prior knowledge about the gaseous products of boiling water. The student receives the new information that the product does not catch fire and instead extinguishes the flame and processes this information in one of several ways. First, when a student encounters the new information, it is analyzed using the person's prior knowledge. This new information is filtered through the schema (index cards) in the long-term memory as the student attempts to make sense of it. This filtering process determines which sensory input is attended to and which memories are activated so the learner can construct meaning for the new information. During assimilation (Appleton, 1989, 1993), the student recognizes that her or his prior knowledge either provides a plausible explanation for the new information (identical fit) or it does not (incomplete fit). If the student experiences identical fit, the student may leave the learning environment with either the correct idea (they already knew boiling water forms steam) or a wrong idea (they still assume boiling water forms hydrogen and oxygen) confirmed. In either scenario, learning has not occurred (Figure 2, Exit 1). The other option is that the student recognizes that the new information gained from the demonstration conflicts with the student's prior knowledge – an incomplete fit between the new ideas and the student's prior knowledge which generates disequilibrium (Appleton, 1989, 1993). In other words, the student becomes uncomfortable with his or her understanding of what is happening when water boils. In this learning model, this disequilibration process must take place for real learning to occur.

During this process, there are several outcomes that may occur. For example, the student recognizes but could choose to ignore the conflict between the new information and his or her prior knowledge, leaving the learning environment with his or her misconception unchanged. As illustrated in the learning model (Figure 2, Exit 4), the student opts out of learning. He or she gives up, often out of frustration, maintaining his or her incorrect understanding that the products of boiling water are hydrogen and oxygen. Another possibility is that the student recognizes there is a conflict between his or her prior knowledge and the new information and the learner restructures his or her prior knowledge, leading to accommodation. Restructuring his or her schema about the vapor from boiling water being steam provides the learner with the proper understanding of the concept and corrects the student's misconception that the products of boiling water were hydrogen and oxygen. This understanding that boiling water produces water vapor brings the learner back into equilibrium (Figure 2, Exit 2). It should be noted that Exit 2 is often an iterative process and rarely happens the first time (Phelps, personal communication, August 30, 2019). Another possible result of disequilibrium is false accommodation. False accommodation occurs when the learner somehow determines the right answer, but fails to restructure his or her prior knowledge to fit the new information (Appleton, 1989, 1993). One form of false accommodation is when the student has committed the correct new knowledge to long-term memory (schema) and uses it only in the classroom (compartmentalization). The student's prior knowledge indicates boiling water produces hydrogen and oxygen gas in spite of the fact that the demonstration shows boiling water produces steam. When asked in a learning environment what is the product of boiling water, the student would respond that it is water vapor although he or she still thinks that it is really hydrogen and oxygen. The student now has the right answer for the classroom yet maintains the misconception in his or her schema (Figure 2, Exit 3).

The information processing model of learning. Another way to think about why students have difficulty with learning and develop misconceptions about chemical concepts is to examine the information processing model of learning. Carlson, Chandler, and Sweller (2003) focused on the limited capacity of working memory as a reason why students have difficulty learning certain topics, while Johnstone (1993, 2006, 2010) specifically applied this theory to the difficulty students have when learning chemistry. Figure 3 provides an illustration of the cognitive pathways involved in Johnstone's description of the information processing model.

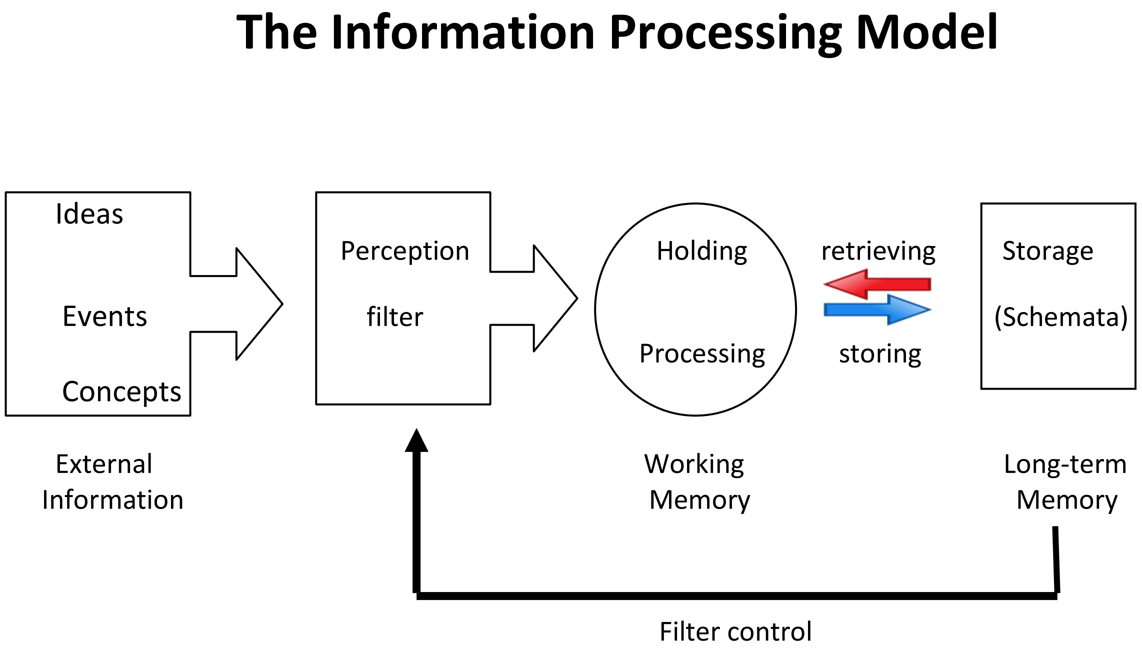


Figure 3. Johnstone's information processing model. Adapted from "You can't get there from here," by A. H. Johnstone, 2010, *Journal of Chemical Education*, *87*, p. 23.

The first step of this model shows external information (ideas, events, and concepts) coming through the senses of the learner that needs to be attended to. The entering information that the learner chooses to attend to, perceive, and decode is filtered through the schemata in the long-term memory, which helps the learner select the important information (the perception filter). Once the learner chooses to act on this important information, it is encoded to be stored in the long-term memory or changed into a response (Johnstone, 1993). The area where information is held, decoded, encoded, matched, and linked is called the working memory (Figure 3). As opposed to the long-term memory, which has a seemingly unlimited capacity, the working memory has a limited capacity and is easily overloaded. Long-term memory is where the learner keeps storage networks, isolated ideas, techniques, episodes, misconceptions, and misinterpretations. Although the long-term memory has unlimited capacity, the retrieval system does not always seem to be very efficient as learners seem to forget or cannot find things from time to time (Johnstone, 1993). Based on the information processing model, Carlson, Chandler, and Sweller (2003) and Johnstone (1993, 2006, 2010) proposed that any cognitive overload of the working memory, which is an integral part of learning, would impede the construction of knowledge in the correct schema. In other words, cognitive overload of the working memory can prevent proper manipulation or characterization of incoming information. Additionally, cognitive overload of the working memory can lead to frustration and opting out of learning (Figure 2, Exit 4).

Three representational levels of chemistry. Johnstone (1993, 2006, 2010) proposed that chemical phenomena can be described using three conceptual or representational levels. These conceptual levels of chemistry are commonly referred to as the macro (macroscopic), symbolic, and molecular (particulate) representations or levels. The macroscopic level is the tangible and visible aspect of chemistry based on the five senses, such as observing the blue color of a copper (II) nitrate solution or weighing out a given amount of copper (II) nitrate. The molecular level is the invisible aspect of chemistry involving atoms, molecules, and ions; for instance understanding that the blue color of a copper (II) nitrate solution is a result of hydrated copper (II) ions in solution. The symbolic level includes the use of symbols, such as balanced chemical equations that represent chemical reactions, chemical formulas that represent atoms and molecules (i.e. $Cu(NO_3)_2$ for copper (II) nitrate), mathematical calculations, formulas and graphs that allow for the interpretation of chemical data. The interconnection between these representational levels of chemistry is illustrated using the triangle in Figure 4.

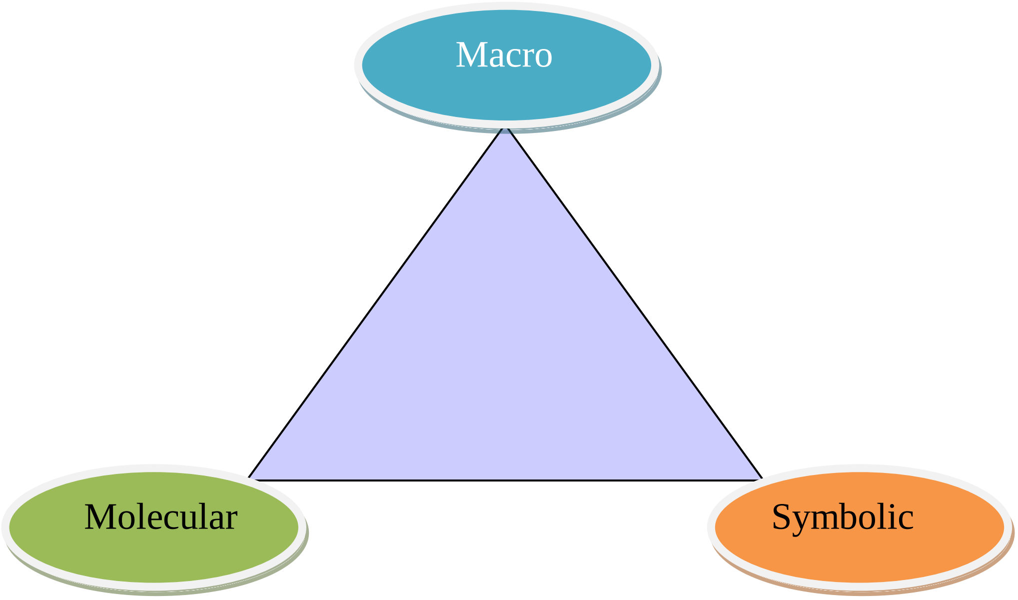


Figure 4 . The three conceptual levels of chemistry. Adapted from “You can’t get there from here”, by A.H. Johnstone, 2010, *Journal of Chemical Education*, 87, p. 24.

The sides of the triangle represent events that involve some mixture of the two levels at either side of the line. For instance, a demonstration of the reaction between aqueous silver nitrate and copper metal that was then interpreted using the balanced chemical equation for the reaction would lie someplace on the side of the triangle between the macro and symbolic corners. A point in the center of the triangle would represent an instance where all three levels were simultaneously and equally used (Johnstone, 2006).

Students have difficulty understanding and learning chemistry (Sirhan, 2007) and part of this might involve a difficulty in operating within the chemistry triad.

Gabel, (1999), Gilbert & Treagust (2009), and Johnstone (2010) believe that this difficulty may be due to the stress that these three conceptual levels of chemistry place on the novice learner's limited working memory. Experts in the field of chemistry, on the other hand, do not seem to exhibit difficulty in operating within the three conceptual levels of chemistry. This suggests that expert chemists have developed the ability to characterize the three levels of representation into scientifically accurate schema within their long-term memory despite their own limited working memory (Johnstone 2006; Kozma & Russell, 1997; Suits, 2015). So how can chemistry educators help novice chemistry learners develop the ability to move among the three conceptual levels of chemistry and generate scientifically accurate schema?

Enhancing student learning. One goal for chemistry educators is to help students achieve proper accommodation of the new knowledge coming into their long-term memory. Although misconceptions among chemistry students are prevalent, there could be other reasons why students opt out of learning or to develop false accommodations. Researchers studying misconceptions often provide interventions useful for correcting student misconceptions of chemical concepts. For instance, Appleton (1993) listed nine teacher interventions, derived from his learning model, that were designed to help students re-categorize science concepts: Identifying preconceptions held by the students, choosing a new encounter that allows for first-hand exploration and is motivating, determining which ideas students are connecting to and focusing on, challenging incorrect ideas, avoiding false accommodation, preventing students from opting out, helping with accommodation, applying new ideas, and diagnosing ideas students have formed and developing strategies to bring about accommodation. On the other hand, Johnstone (2010) believed the chemistry topics that instructors use as a starting point should be changed. Instead of starting with atoms and electronic structure (which can be very abstract), he suggested starting with materials, such as gasoline, plastics, and clothing, that students have a familiarity with (prior knowledge of) and interest in.

Computer technology can also be used to combat the misconceptions and misunderstandings of chemistry concepts and enhance student understanding and learning of chemistry (Kelly, Phelps, & Sanger, 2004; Sanger, Campbell, Felker, & Spencer, 2007; Sanger, Phelps, & Fienhold, 2000; Williamson & Abraham, 1995). Specifically, this study examines the role of the visual images used in animations for improving students' interpretations of the oxidation-reduction process by identifying which visual components of an oxidation-reduction animation are useful for improving students' interpretation and understanding of the oxidation-reduction process.

Visualizations. A visualization is "a mental image that is similar to a visual perception" (Vocabulary.com Dictionary, n.d.). Chemical visualizations have the ability to aid learners in developing mental models (images), mental schemes, or as Mayer (2009) describes them, pictorial models of the chemical phenomena being addressed, especially if the animation uses visual images at the particulate (molecular) level. In her work on the Particulate Nature of Matter (PNM), Williamson (2008) defined mental models (images, schemes, pictorial models) as "the pictures we 'see' in our mind when we are thinking about something" (p. 68). Williamson (2008) also noted that it is easier for a person to develop and retain the mental model of a visible object than it is to develop a mental model of something that is not visible. Suits (2015) defined mental models as “a set of mental representations and the mental operations that adapt these representations to a particular problem” (p. 596). These mental models facilitate the organization of incoming information into meaningful schema that allow the learner to select and transform information and develop explanations of what they observed (Suits, 2015). Particles such as atoms and molecules are not visible; therefore, the development of mental models representing these objects and their interactions poses difficulty for many chemistry learners. Furthermore, not everyone creates the same mental model of a concept; for instance, the mental models of experts and novices differ. In one study, experts and novices were asked to group a number of different chemistry representations in a manner that made sense to them (Kozma & Russell, 1997). The researchers determined that experts were better at grouping the representations than novices because the experts’ groupings were based on their more complete conceptions of the representations; the novices’ groupings, however, were based on their limited conceptions of the representations and focused more on the surface features than those of the experts (Kozma & Russell, 1997). Experts have the ability to develop proper mental models of chemical processes based on their long and varied experiences with the material. Their experiences with chemistry concepts also aid the experts in placing the characterizations of the three representational levels of chemistry (macroscopic, symbolic, and particulate) into the correct mental categories (Kozma & Russell, 1997). These mental images and their links to the experts’ mental representations make the experts better at solving complex problems because they have the ability to move from one representation to another (Suits, 2015). Additionally, experts have developed the ability to adapt incorrect characterizations of concepts and accommodate new information into their existing schema in ways that facilitate understanding and learning. As Mulford and Robinson (2002) stated: “It may be that those of us who are older [more experienced] have worked our way through these alternate conceptions” (p. 742). The focus on surface features of a representation by novices has been given as another reason for the difficulty students have in learning and understanding chemistry (Suits, 2015). Johnson (1998) found that students’ particulate mental models could be placed on a continuum progressing from having no conception of particles making up a substance on one side to an understanding of the role particles have in providing a substance with its macroscopic characteristics on the other.

Visualizations can also aid in reducing the mischaracterization of chemistry concepts into the wrong mental categories that often lead to the development of misconceptions among students. In a study relating spatial skills and visualization, Pribyl and Bodner (1987) found that students who drew correct figures while answering organic chemistry questions were less likely to give incorrect answers than those students who did not draw figures or drew incorrect figures. It appeared that these self-generated diagrams aided memory and helped students form mental models useful in the problem-solving process. Kozma, Chin, Russell, and Marks (2000) reported that it is common practice for chemists to draw and sketch various aspects of chemical phenomena when solving chemistry problems. These sketches and drawings represent a spatial language that involves two-dimensional geometry and representation of the particulate nature of matter (PNM). These images supply details of the chemical process that may not have been apparent to the learner otherwise. Drawings and sketches are also likely to aid chemists' visual thinking and give them the ability to better represent information (Wu & Shah, 2004). Several researchers have demonstrated that drawings can be useful in identifying misconceptions at the particulate level (Brandriet, 2014; Cardak, 2009; Davidowitz, Chittleborough, & Murray, 2010; Naah & Sanger, 2012). Drawings and sketches of chemical phenomena, however, are not the only visualization techniques available to aid students in learning. Physical molecular model kits, textbook illustrations, videos, graphs, teacher demonstrations with concrete models, role-playing, computer animations, and simulations have also been cited as tools that can be used to help students characterize chemical concepts into the proper mental category (Kozma & Russell, 1997; Williamson, 2011; Williamson & Abraham, 1995; Wu & Shah, 2004).

Static drawings and sketches can have a role in helping students visualize the PNM and this can lead to a better understanding of chemical processes. Since this dissertation studies the effect that animations can have on students' understanding of a chemical process, this might be a good place to address whether animations that show visual images and their motions at the particulate level have an advantage over static drawings and sketches in helping students understand chemistry. Hoffler and Leutner (2007) conducted a meta-analysis of 21 studies that yielded 76 pair-wise comparisons of animations and static drawings. In their analysis, the authors found that when computer animations are representative (applicable to the topic to be learned) and realistic (the four levels of realism are: schematic, rather simple, rather realistic, and photo-realistic), they are better than static pictures in the development of student understanding. However, when animations are decorative or unrelated to the topics to be learned, they do not have an advantage over static pictures in the learning process. Additionally, it was found that animations are more effective in the acquisition of procedural-motor knowledge and problem-solving knowledge (Hoffler & Leutner, 2007). In an expansion of Hoffler and Leutner's (2007) meta-analysis, Berney and Betrancourt (2016) performed a meta-analysis of 61 primary studies that yielded 140 pair-wise comparisons of animations and static pictures that included more than 7000 subjects; their results largely supported the findings of Hoffler and Leutner (2007). Berney and Betrancourt (2016) found that using animations in instruction led to higher learning gains than when using static pictures. In terms of learning outcomes, animations were more effective at helping students learn factual and conceptual knowledge and helping them remember, understand, and apply information than static drawings and sketches. Furthermore, when there was no accompanying information (narration) with the animation, there was a strong animation effect (Berney & Betrancourt, 2016), which is relevant to the research studies presented in this dissertation since they used non-narrated animations. Additionally, when Berney and Betancourt (2016) specifically examined chemical education research studies, they found that animations were superior to static images in producing learning gains.

Computer animations of chemical processes. Mayer and Moreno (2002) described an animation as a simulated motion picture showing the movement of drawn objects. Animations are a type of pictorial representation that has been artificially put together through successive drawings that differ slightly from each other. Some animations, such as cartoons, have been created for entertainment purposes; however the animations used in most chemical educational research studies are designed to depict chemical processes or events for educational purposes. As Suits (2015) stated:

> … the goal of dynamic visualizations is to get chemistry students to visualize on the computer screen (i.e., external representations) the same types of representations of chemical phenomena that chemists mentally envision (i.e., internal representations). (p. 595)

Williamson and Abraham (1995) studied the effect of computer-generated animations on students' understanding of chemical concepts involving the PNM. Their study set out to determine if the use of computer animations changed the learning environment in the chemistry classroom and laboratory compared to instruction using static pictures in the following areas: Understanding of the PNM, improved course performance, enhanced student attitudes towards instruction of the PNM, and differential changes in conceptual understanding based on reasoning ability. The major result of the study was that students who viewed animations showing the particulate behavior of a chemical process improved their conceptual understanding and had fewer misconceptions than students viewing static visuals, regardless of the extent of their exposure to the animations. These researchers also found that animations improved conceptual understanding because the students who viewed the animations formed better mental models of the particle nature of chemical processes (Williamson & Abraham, 1995). Other research studies support the findings of Williamson and Abraham (1995). For example, Sanger, Phelps, and Fienhold

(2000) gave a group of students traditional instruction on the behavior of gas particles using static pictures at the particulate level in a can-crushing demonstration followed by a quiz asking the students what would happen in a similar event. These researchers found that the students had many misconceptions and difficulties explaining the demonstrated event, including the blind use of gas laws to explain the event and ignoring the importance of the condensation of water vapor. Another group of students were taught using the same can-crushing demonstration with the addition of a particulate-level computer animation of the chemical event. This group performed better on the follow-up quiz and were more likely to avoid the blind use of gas laws, more likely to mention the condensation of water vapor, and more likely to provide a completely correct explanation of the demonstration. In a subsequent study, Kelly, Phelps, and Sanger (2004) used the same can-crushing demonstration animation created for the study above to examine secondary students’ conceptual understanding of the demonstration at the macroscopic, microscopic and symbolic representational levels of chemistry. The treatment group that viewed the can-crushing animation and the control group that did not view the can-crushing animation were taught by two different teachers with similar educational backgrounds and teaching styles. This study demonstrated that not only can computer animations of a chemical process improve students’ understandings of the particulate nature of chemistry, but computer animations can also improve students’ understandings of the macroscopic and symbolic representations of chemistry (Kelly, Phelps, & Sanger, 2004). In another study, Sanger, Campbell, Felker, and Spencer (2007) created an animated version of a famous multiple-choice conceptual question based on static particle diagrams relating to gas behavior (Nurrenbern & Pickering, 1984). The students were given the conceptual question with static diagrams and were asked to choose the correct answer from four possible choices as the pretest. Each student was then allowed to view the animated version of the static question for a 5-10 minute time period. After viewing the animation, the students were given the same multiple-choice conceptual question as a posttest. The results from this study indicated that viewing the animations helped students provide more correct answers on the posttest than on the pretest. Furthermore, the vast majority of the students with correct answers on the pretest did not change their answers on the posttest after viewing the animation. A study by Yang, Andre, Greenbowe, & Tibble (2003) focusing on the impact of animations on learning electrochemistry demonstrated that psychology students who viewed dynamic animations about batteries and flashlights had a better understanding of these materials than those students who viewed static diagrams of batteries and flashlights. In general, researchers have determined that using animations, characterized under the broad sense of the definition of computer simulations, leads to a large improvement in conceptual understanding of the invisible (Rutten, van Joolinger, & van der Veen, 2012).

Akaygun (2016) investigated and compared students' static and dynamic representations of their mental models for an atom. The study had students draw static representations of the structure of the oxygen atom using storyboards both before and after they generated and explained a dynamic animation of the oxygen atom using an animation-developing software program. Additionally, the students were asked to give a two to three minute explanation of their animation. Akaygun found that the students' final static representations of their mental model of the oxygen atom were more refined and more accurate after creating the animation than their initial static representations of the oxygen atom. She also noticed that students included more dynamic features in their final static drawing of the oxygen atom. In another study, Yaseen (2018) investigated the effect that student-generated animations had on their understanding of the states of matter. Through a series of activities that included a pre- and post-test, group production of an animation depicting the states of matter, group discussions, viewing and critiquing both student-generated animations and expert animations, and semi-structured interviews, Yaseen found that students improved their understanding of the states of matter as a result of these interventions that included student-generated animations. Students also felt that they would have been unproductive learners without participating in the development of an animation that allowed them to express their own concepts regarding the states of matter (Yaseen, 2018).

Visualization techniques (such as animations) allow the learner to form particulate mental models of a chemical process, providing the learner with the ability to reason about particulate behavior of that process (Williamson, 2011). Since computer-generated animations improved students' understandings of the behavior of gases, states of matter, and electrochemistry, it should stand to reason they could also improve students' understandings of oxidation-reduction reactions.

Identifying student misconceptions related to oxidation-reduction reactions. Since electrochemistry is a difficult topic for many students, it should not be a surprise that a large number of student misconceptions in electrochemistry have been identified, especially related to the topic of oxidation-reduction reactions (Brandriet & Bretz, 2014b; Garnett & Treagust, 1992; Österlund, et al., 2010; Rosenthal & Sanger, 2012; Schmidt &Volke, 2003). Garnett and Treagust (1992) identified a series of misconceptions about the oxidation-reduction process held by senior high school students in Australia. A list of those misconceptions can be found in Figure 5.

Assigning oxidation states

The oxidation state of an element is the same as the charge of the monatomic ion of that element.

Oxidation numbers or states can be assigned to polyatomic molecules and/or polyatomic ions.

The charge of a polyatomic species indicates the oxidation state of the molecule or ion.

Identifying oxidation-reduction equations using oxidation numbers

In an equation, changes in the charges of polyatomic species can be used to identify oxidation-reduction equations.

In an equation, changes in the charges of polyatomic species can be used to determine the number of electrons removed from, or gained by, reacting species.

Using other definitions to identify oxidation-reduction equations

In all chemical equations, the definitions of oxidation as the addition of oxygen, and reduction as the removal of oxygen, can be used to identify oxidation and reduction.

The interdependence of oxidation and reduction processes

Oxidation and reduction processes can occur independently.

Figure 5. Misconceptions about the oxidation-reduction process held by high school seniors. Adapted from “Conceptual Difficulties Experienced by Senior High School Students of Electrochemistry: Electric Circuits and Oxidation-Reduction Equations,” by P. J. Garnett & D. F. Treagust, 1992, *Journal of Research in Science Teaching*, *29*, p. 138.

Garnett and Treagust concluded that some of these misconceptions could be corrected if a single definition was used for oxidation and reduction. Schmidt & Volke (2003) also advocated for the use of a single definition for oxidation and reduction to help reduce student misconceptions. In their study, Schmidt and Volke (2003) argued that the formation of misconceptions regarding the oxidation-reduction process could be the result of the changing and evolving definitions of oxidation and reduction throughout history. One result of their study was the identification of the misconception that oxidation required the transfer of oxide ions, which confirms a similar misconception identified by Garnett and Treagust (1992). However, using a single definition of oxidation and reduction may be difficult as Österlund, Berg, and Ekborg (2010) discovered. Their research examined the definitions of oxidation and reduction found in textbooks. They found that there are four definitions used in the various branches of chemistry: The electron model (gain and loss of electrons), the oxidation number model (decrease and increase in oxidation numbers), the hydrogen model (gain and loss of hydrogen), and the oxygen model (loss and gain of oxygen). The electron and oxidation number models are used in introductory and inorganic chemistry while the hydrogen and oxygen models are used in organic chemistry and the hydrogen model, oxygen model, and electron model are all used in biochemistry. Since the use of these models of oxidation and reduction varies for each branch of chemistry, it makes it difficult for the novice chemistry learner to fully understand the concepts of oxidation and reduction, Österlund, Berg, & Ekborg (2010) recommended that textbook authors should help students move between the different redox models.

Brandriet and Bretz (2014a, 2014b) conducted a study examining students' understandings of the three representational levels of chemistry with regard to the oxidation-reduction process. These authors identified six major misconception themes that students held about oxidation-reduction reactions: (1) Oxidation numbers: In some cases, students had the misconception that in an oxidation-reduction reaction there is no change in the charge of the species during the reaction. (2) The surface features of oxidation-reduction reactions: For example, students did not identify a reaction as an oxidation-reduction reaction because the reaction was also a combination reaction. (3) Role of the spectator ion in the oxidation-reduction process: Students believed that the cation was bonded to the spectator anion in solution or that the spectator anion also acted as the facilitator for the reaction because the spectator anions attracted the metal cations away from the solid metal. (4) The electron transfer process: The understanding of where and how electrons were transferred in the reaction was negatively impacted by misconceptions about how the atoms, molecules, and ions were interacting during oxidation-reduction reactions. Additionally, many students believed that electron transfer occurred when bonds were broken and formed and when a reacting cation and spectator anion interacted because cations lost electrons and anions gained electrons. (5) The dynamic reaction process: Students believed that the reacting cation pushed the new cation off the solid metal and into the solution so there would be room for the first metal cation to be deposited on the solid metal surface as a metal atom. (6) Electrostatics and bonding: Students believed that charges from one reacting cation were used to replace charges that were missing when the new cation left the surface of the solid. Brandriet &

Bretz (2014a, 2014b) hypothesized that the students tended to view the process in steps rather than seeing the oxidation-reduction process as continuous. These researchers also concluded that these misconceptions were a result of flawed mental models of the oxidation-reduction process held by the students. Their remedy for these misconceptions was to have students draw or sketch the oxidation-reduction process in order to build better mental models.

The use of computer animations in understanding oxidation-reduction reactions. Animations are another useful avenue to minimize student misconceptions and to help students develop correct mental models of chemical processes. Greenbowe (1994) described the use of animations in the teaching of electrochemical cells. Animations, Greenbowe asserted, were useful for showing the dynamic particulate aspects of these cells and the oxidation-reduction reaction itself. He also noted that for students to make connections between the particulate nature and the visible nature of an electrochemical cell, they needed to view macroscopic demonstrations of these types of cells as well. In an effort to diminish the number of students holding the misconception that electrons flow through the salt bridge of an electrochemical cell, Sanger and Greenbowe (1997b) used animations of an electrochemical cell along with lecture. The results of their study demonstrated that the use of animations along with lecture reduced the number of students who held the misconception that electrons flow through the salt bridge.

Through the use of animations created by Roy Tasker as part of the VisChem project (Tasker & Dalton, 2006), Tasker and Dalton demonstrated that students produced more “scientifically acceptable ‘key features’” (p. 145) in their drawings of chemical processes. Evaluation of student-generated drawings provided evidence that students developed better mental models of the chemical process they were asked to draw. In addition, Tasker and Dalton (2006) demonstrated that students were able to transfer conceptual ideas gained from the animations to new situations, which is a reliable measure of understanding (Mayer, 2009). Furthermore, students who had viewed the VisChem animations earlier in their academic career felt that the animations helped them with chemistry concepts as they progressed through their degree program (Tasker & Dalton, 2006). It should be noted that the VisChem project is more than just a series of animations. The project uses a seven-step learning design process to design instruction including animations. It appears that animations can help reduce misconceptions by improving students’ mental models of chemical processes and improving the connections between the conceptual levels of chemistry – macroscopic, particulate, and symbolic.

Rosenthal and Sanger (2012) used an unnarrated version of Tasker’s VisChem animation of the oxidation-reduction reaction between solid copper metal and aqueous silver nitrate along with an animation of the same reaction with less realistic three-dimensional features (also unnarrated) developed by Sanger to examine students’ understanding of the oxidation-reduction process. Screenshots for both of these animations appear in Figure 1. In this study, the researchers found that students misinterpreted several of the symbolic visual representations used in these animations (Figure 6). These misinterpretations ranged from students not understanding that valence electrons affect the size of the metal atom to students thinking that the blue sphere used to depict the nitrogen atoms in the nitrate ions caused the blue color in the aqueous solution. Rosenthal and Sanger (2012) also identified many misconceptions students had about the oxidation-reduction process, that including that cations and anions are attached or bonded together as ion pairs in water, silver ions and copper atoms react in a 1:1 ratio, and nitrate ions in this reaction exhibit a -2 charge.

Student misinterpretations identified in the Rosenthal and Sanger study

Outer valence electrons are not part of a metal atom and do not affect size.
The red-white shapes represent nitrate ions, so nitrogen atoms are drawn as red and the oxygen atoms are drawn as white.
The blue-red clusters represent molecules.
Cations and anions are attached or bonded together as ion pairs in water.
There are more silver ions than nitrate ions before the reaction.
There are more nitrate ions than silver ions before the reaction.
Nitrate ions in this reaction have a -2 charge.
The silver ions and copper ions react in a 1:1 ratio.
The silver ions and copper atoms react in a ratio greater than 2:1.
An unspecified number of electrons are transferred from copper to silver.
Gaining or losing electrons will not change the size of the atom or ion.
Water molecules force the reaction to occur by bringing the silver ions to the surface to react and pulling the copper ions away from bulk metal.
The behavior of the nitrate ions drive this reaction – this reaction occurs because the nitrate ions are more attracted to the copper ions than silver ions.
The combination of copper and nitrate ions are causing the blue color in the aqueous solution.
The blue sphere in the blue-red cluster is causing the blue color in the aqueous solution.

Figure 6. A list of students' misinterpretations after viewing two different animations picturing the oxidation-reduction reaction between aqueous silver nitrate and copper metal. Adapted from "Student Misinterpretations and Misconceptions Based on Their Explanations of Two Computer Animations of Varying Complexity Depicting the Same Oxidation-Reduction Reaction," by D. P. Rosenthal & M. J. Sanger, 2012, *Chemistry Education Research and Practice, 13*, p. 475.

The complete list of misconceptions identified in the Rosenthal and Sanger study (2012) is provided in Figure 7.

Student misconceptions identified in the Rosenthal and Sanger study

Outer valence electrons are not part of a metal atom and do not affect its size.
The valence electrons in a metal represent molecular forces or bonds.
The red/white shapes represent nitrate ions, so nitrogen atoms are drawn as red and oxygen atoms are drawn as white.
Cations and anions are attached or bonded together as ion pairs in water.
There are more silver ions than nitrate ions before the reaction.
There are more nitrate ions than silver ions before the reaction.
Silver ions in this reaction have a +2 charge.
Nitrate ions in this reaction have a -2 charge.
Copper ions in this reaction have a +1 charge.
The charge of a cation is determined by counting the number of nitrate ions around it.
The silver ions and copper atoms react in a 1 : 1 ratio.
When electrons are transferred from copper to silver, the charges of these species do not change.
The behavior of the nitrate ions drives this reaction—this reaction occurs because the nitrate ions are more attracted to the copper ions than the silver ions.
The combination of copper and nitrate ions are causing the blue color in the aqueous solution.
The blue sphere in the blue/red cluster is causing the blue color in the aqueous solution.
The particulate depictions in the animations are a direct representation of the macroscopic properties of the substances present.

Figure 7. A list of students' misinterpretations after viewing two different animations picturing the oxidation-reduction reaction between aqueous silver nitrate and copper metal. Adapted from "Student Misinterpretations and Misconceptions Based on Their Explanations of Two Computer Animations of Varying Complexity Depicting the Same Oxidation-Reduction Reaction," by D. P. Rosenthal & M. J. Sanger, 2012, *Chemistry Education Research and Practice, 13,* p. 476.

It should be noted that many of the students' misinterpretations were also listed as student misconceptions – the misinterpretation of a visual image in an animation was deemed to be a misconception when a student tried to apply the behavior of the misinterpreted visuals to the properties and behaviors of the particles in the reaction. The authors pointed out that some of these problems students had in interpreting the animations were due to gaps in the students' propositional knowledge. Also, some of their participants exhibited conflation of the particulate representations depicted in the animations and the macroscopic properties of the chemicals involved in the oxidation-reduction reaction. An example of this conflation was that some students believed that the blue sphere in the animation (a particulate view) was responsible for the blue color of the solution (a macroscopic view). This conflation of distinct concepts that have some similar characteristics into one concept while viewing animations has been reported before (Andersson, 1986; Ben-Zvi, Eylon, & Silberstein, 1986; Kelly & Jones, 2008; Sanger, Brecheisen, & Hynek, 2001). Rosenthal and Sanger (2012) believed some of the misconceptions in their study were possibly a result of this confusion. Furthermore, the researchers demonstrated that students had more difficulty interpreting the more complex animation due the extraneous visual material included in the more complex animation.

Rosenthal and Sanger (2013a) also examined students' particulate-level explanations of the copper metal and aqueous silver nitrate oxidation-reduction reaction based on the order in which the students viewed the two oxidation-reduction animations shown in Figure 1. An order effect was found in that students' explanations of the oxidation-reduction reaction were better for those students viewing the more complex animation first followed by the simpler animation compared to students who viewed them the other way around. Students in that first group exhibited better understandings of the electron transfer process, size changes in the atoms and ions, the source of blue color in the solution, the fact that water is not the driving force of the reaction, and the overall balanced equations for the reaction. The researchers also found that students had difficulty in applying concepts viewed in one animation to the depictions of the same process shown in the other animation. Additionally, students reported that it was easier to interpret the more simplified animation because of its iconic nature – showing the charges of atoms and ions, showing the loss of two electrons by each copper atom and the gain of one electron by each silver ion, showing the 2:1 reacting ratio of the silver ions and copper atoms, showing the size changes that occurred when atoms and ions lost and gained electrons, and showing that the solution became darker blue when a copper ion was released into the solution. Including this type of information in the animation improved students' explanations of the more simplified animation compared to the more complex one (Lee, Plass, & Homer, 2006; Rosenthal & Sanger, 2013a).

In an analysis of how viewing one animation of an oxidation-reduction reaction affects students' interpretations of another animation of the same oxidation-reduction reaction, Rosenthal and Sanger (2013b) found when students viewed the more complex animation before viewing the more simplified animation there was no statistically different effect on students' explanations of the oxidation-reduction process; however, there was a small improvement in the students' ability to write a balanced chemical equation for the reaction. When students viewed the more simplified animation followed by the more complex animation, however, their explanations of the 1:1 silver ion to nitrate ratio, the 2:1 silver ion to copper atom ratio, the electron transfer process, and the writing of the balanced equation for the oxidation-reduction reaction improved. The authors suggested that this improvement was a result of the ease with which students could interpret the more simplified animation, thus reducing student confusion and distraction. Furthermore, Rosenthal and Sanger (2013b) noticed that viewing the more simplified animation before the more complex animation actually worsened students' explanations of the source of the blue color in the solution. In regard to this negative effect, Rosenthal and Sanger believed that since the more simplified animation detailed the solution's color change, students expected this type of detail in the more complex animation and were confused when the more complex animation did not depict any visual information related to the color change. Although Rosenthal and Sanger's (2012) first study supported Tasker and Dalton's (2006) observation that even with the use of animations some students will continue to misinterpret and maintain misconceptions, it is clear, when all three of Rosenthal and Sanger's studies (2012, 2013a, 2013b) are examined, that students seemed to develop a better understanding of the oxidation-reduction process after viewing the more simplified animation.

Kelly, Akaygun, Hansen, and Villalta-Cerdas (2017) had first semester chemistry students view and critique two animations of the aqueous silver nitrate and copper metal oxidation-reduction reaction. One of the animations used was created to be scientifically accurate while the other was created to be scientifically inaccurate. The scientifically accurate animation is the narrated version of Tasker's VisChem animation used by Sanger and Rosenthal (Figure 1b). The scientifically inaccurate animation depicted the ionic silver nitrate as two neutral molecules moving rapidly with the nitrate ends aimed toward the copper metal lattice. Upon collision with the copper lattice, the silver nitrates break apart with the two silvers staying on the lattice surface and the two nitrates attaching to a copper atom from the lattice surface and leaving the surface as a copper nitrate molecule that is then depicted as going into solution. It should be noted that in this animation, the charges on ionic species where not depicted and that only two water molecules were depicted moving in the background without interacting with any other species (Kelly, Akaygun, Hansen, & Villalta-Cerdas, 2017).

Before viewing the two animations, students in the Kelly et al. (2017) study were asked to provide a molecular level explanation of the reaction. When the students' self-generated drawings and oral explanations were analyzed, the researchers found four difficulties the students had depicting and explaining oxidation-reduction reactions at the molecular level: They had difficulty representing the molecular level without using macroscopic level events; they failed to properly distinguish chemical species in the reaction and confused or conflated atoms, ions, and molecules in their drawings and explanations; they misrepresented the spacing between the chemical species; and they could not identify the chemical species that brought about the macroscopic change. These challenges were a result of the students trying to imagine, draw and explain the abstract nature of what they could not see as well as not having a good understanding of what substances were involved in or what caused the reaction and how these chemical species led to the solution's color change (Kelly et al., 2017). After viewing the two contrasting animations of the same reaction, students' explanations of the molecular level process were analyzed as before. The results indicated that the students maintained the same difficulties in representing the molecular level as they had before viewing the animations. Students also continued to emphasize the macroscopic level in their molecular level drawings and explanations. However, students' representation of the oxidation-reduction reaction improved in the following areas: The representation of chemical species; the representation of the spacing between atoms in the copper lattice; and the identification of the chemical species formed in the reaction (Kelly et al., 2017).

Overall, students adjusted their representations of the reaction to fit what they viewed in both animations because they believed both animations were scientifically accurate. Even after viewing the animations, students seemed to maintain uncertainties about their representations. This may be a due to the fact that the representation did not fully account for the macroscopic evidence provided and/or the representation not aligning with the students' prior knowledge. The students in this study were also asked to critique each of the animations to determine their scientific accuracy and to choose which animation was scientifically accurate. More than half of the students correctly identified the scientifically accurate animation, yet half of the students revised their drawings to fit with the scientifically inaccurate animation. All of the students believed that both animations were correct and would be useful in understanding the important features of the oxidation-reduction reaction (Kelly et al., 2017).

The Theoretical Basis for the Research

One of the theoretical underpinnings of the research in this dissertation is the cognitive load theory (Sweller, 1994; Sweller & Chandler, 1994), which posits that learning is negatively impacted when the cognitive load of the instruction exceeds the capacity of the learner's working memory. The working memory capacity can be exceeded when there is a high interrelationship between the elements of a topic to be learned, such as the relationship between the three conceptual levels of the chemistry triad – the macroscopic, the microscopic (particulate), and the symbolic levels. The powerful long term memory along with schema acquisition and automation can be used to minimize these burdens on the working memory. Thus, the proper design and presentation of instructional materials can play a role in reducing the load on the learner's working memory (Sweller & Chandler, 1994).

Variation theory is a learning theory used to explain why there are differences in the way students interact with the same instructional environment and develop different understandings of the same concept (Bussey, Orgill, & Crippen, 2013; Kelly, 2014); this theory is also a basis for the research in this dissertation. For learners to make sense of a concept being taught, they must notice certain critical features of that concept. This *noticing*, as it is referred to, must include awareness, discernment, and simultaneity (Bussey et al., 2013). For a particular concept or topic, aspects or features of that concept are held in focal awareness. Limitations in the amount of information the brain is able to process make it impossible for the learner to be aware of all aspects of the concept, and so the learner must focus on certain aspects of it. The features in the learner's focal awareness are used to construct knowledge about the lesson (Bussey et al., 2013). Discernment is a product of direct experience requiring the learner to hold features of the concept in focal awareness using their environment to construct a sense of that concept. Understanding a concept also involves the learner's ability to be simultaneously aware (simultaneity) of all of the critical features of the topic being addressed (Bussey et al., 2013).

Another theoretical framework that applies to this study was developed by Lowe and Boucheix (2008) to explain a learner's perceptual and conceptual processing of animations. These researchers believed that much of the existing multimedia learning theories (e.g. Mayer's cognitive theory of multimedia learning) were based on research using static pictures combined with text, which was subsequently applied to animations. However, the presence of temporal change in animations was not included in the development of these theories. In particular, the movement in an animation has been shown to have an influential effect on the way the displayed graphic material is processed (Lowe & Boucheix, 2008). Lowe (2003) found that it was not just the movement occurring in the animation that allowed information to be preferentially extracted by the learner – it was more the dynamic contrasts with visual context in the animation that was noticed by the learner. He further proposed that components of an animation can attract the learner's attention because they change more than their surroundings or because they change less than their surroundings (Lowe, 2003). Lowe and Boucheix (2008) proposed a five-stage model (the animation processing model) describing the perceptual and conceptual processing required to build dynamic mental models from animated content. In phase 1 of the model, the viewer separates the visuals presented in a complex animation into event units that will be used for latter processing – a process that is demanding due to limited cognitive capacity in the working memory. The event units are a compilation of small groups of associated graphic entities used in the cognitive processing step in phase 2. Phase 2 processing uses the event units developed in phase 1 to generate regional structures, called micro chunks. The generation of micro chunks is the result of linking event units through visuospatial characteristics, behavioral characteristics, or other characteristics viewed in the animation. In phase 2, these regional structures are still isolated and not formed into a continuous structure. During this phase, interactions between moving objects that lead to the inference of causal links are possible (Lowe & Boucheix, 2008). In phase 3, the causal links generated in phase 2 are connected, leading to a mental characterization of the components of the animation. This mental characterization is a detailed description of all aspects of the animation that provides the viewer with a mental representation that specifies the behavior of all essential operational parts depicted in the animation. If the learner does not have sufficient prior-knowledge and experience in relationship to the topic of the animation, this may limit the quality of information the learner can retrieve from the animation. These three phases of the animation processing model describe the bottom-up processing required for a learner to begin to construct a high quality mental model of an animation. The next two phases of the animation processing model describe the top-down processing required to generate a high quality mental model. In phase 4, the events that were identified in the first three phases of the animation processing model are characterized into relational structures in domain-specific terms. During this processing, the role of each individual subsystem in the animation is coordinated with the roles of other subsystems in the animation to form an overall functional mental model. In phase 5, animation function is elaborated across a variety of operational requirements to produce a high quality mental model of the animation. It should be noted that novice chemistry learners use only the first three phase of the model in developing their mental models of a chemistry concept while experts in the field use all five phases of the model to develop their high quality mental modes of a chemical concept (Lowe & Boucheix, 2016; Lowe & Boucheix, 2008).

Mayer's (2009) cognitive theory of multimedia learning, which is founded on Paivio's (1986) dual-coding theory and Baddeley's (1986) model of working memory, is also foundational to this research. In the cognitive theory of multimedia learning, it is believed that learners process visual and auditory information through separate cognitive channels, as shown in Figure 8. This is a more detailed explanation of the information processing system shown in Figure 4.

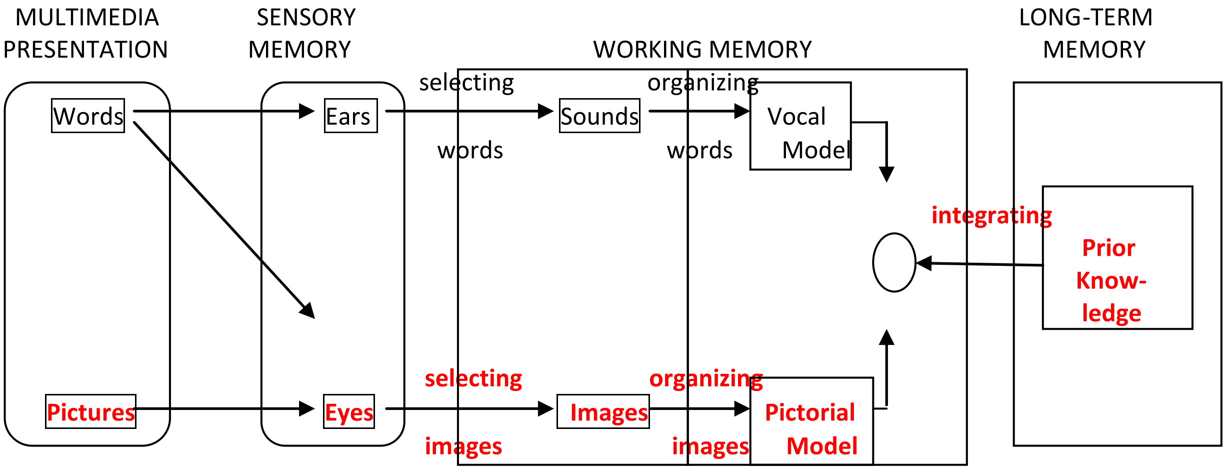


Figure 8. The cognitive processes involved in the selection and organization of relevant images (bolded and in red). Adapted from "Multimedia learning, 2^{nd} ed." by R. E. Mayer, 2009, Cambridge, UK: Cambridge University Press, p. 61.

Each of these cognitive channels has limited processing ability. Further, learning results when relevant information is added to existing mental frameworks (schemata or mental models), through combining new knowledge with prior knowledge (Rosenthal & Sanger, 2012). Based on the information-processing theory of learning (Gabel¸1999; Johnstone, 1997, 2010; Tsarparlis, 1997) and cognitive load theory (Sweller, 1994; Sweller and Chandler, 1994), Mayer’s (2009) cognitive theory of multimedia learning suggests that learners gather external information into their sensory memory and match this information to their prior knowledge, interests, and beliefs before it is available for use in their working memory. Working memory is limited, and is used by the learner to connect new information in the sensory memory and old information stored in long term memory. Multimedia presentations (animations) that lead to concept activation, allowing learners to connect new information with relevant information that has been stored in schema, will help facilitate better student learning (Rosenthal & Sanger, 2013a).

The cognitive theory of multimedia learning also contains a number of corollaries or principles. These principles include the multimedia principle, the spatial contiguity principle, the temporal contiguity principle, the coherence principle, the modality principle, the redundancy principle, and the individual differences principle. Each corollary describes how some aspect of a multimedia presentation can enhance student learning. For instance, the multimedia principle states that students learn better from words and pictures than from words alone. The individual differences principle shows that a well-designed multimedia presentation can preferentially enhance the learning of low-knowledge students compared to high-knowledge students, and is consistent with the tenets of variation theory (Bussey et al., 2013).

Mayer's corollary that is relevant to the water molecules study is the coherence principle. This principle comes from research performed by Mayer's group (2001) showing that student learning was enhanced when extraneous material was left out of a multimedia presentation. Mayer broke the coherence principle into three corollaries: Coherence principle 1 states that student learning can be harmed when interesting yet irrelevant words and pictures are added to a multimedia presentation; Coherence principle 2 states that student learning can be harmed when interesting but irrelevant sounds and music are added to multimedia presentations; and Coherence principle 3 states that student learning is improved when unneeded words are deleted from a multimedia presentation. All three principles cover the effect on student learning when multimedia presentations contain extraneous material in the form of visual, audio, or verbal information (Mayer, 2001). The most relevant of these corollaries to the research described in this dissertation is Coherence principle 1 – the addition of extraneous visual content into an animation may harm student learning. The extraneous visual material competes for mental resources in the working memory and turns a learner's attention away from important information, disrupting the organizational process and preventing the learner from correctly organizing the new information being presented (Dwyer, 1972; Garner, Gillingham, & White, 1989; Harp & Maslich, 2005; Mayer, 2001).

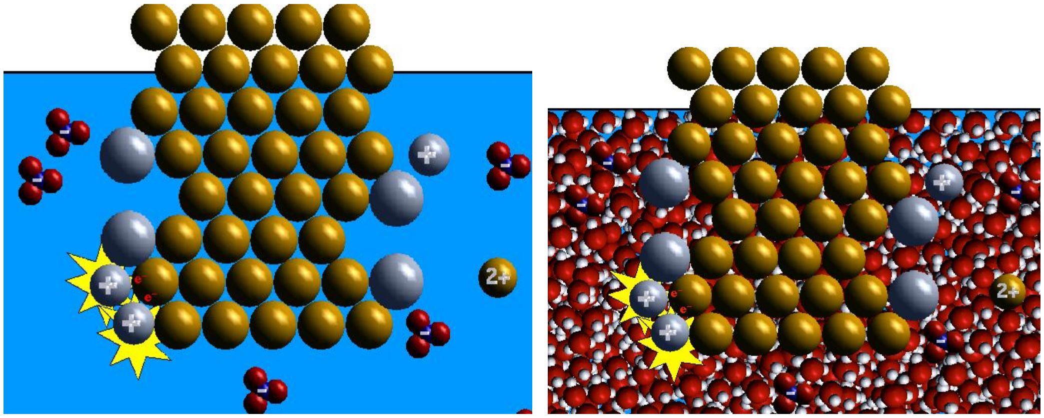
Another of Mayer's (2001) concepts that is relevant for the research described in this dissertation is the steps of active processing described in his cognitive theory of multimedia learning. For learning to occur, Mayer assumed there must be active-processing occurring at the cognitive level. This active processing occurs in five steps or cognitive processes: Selecting relevant words; Selecting relevant images; Organizing selected words; Organizing selected images; and Integrating word-based and image-based representations. These steps are illustrated in Figure 8. The specific cognitive process that is relevant to this dissertation is Selecting relevant images in an animation. The pathway bolded in red shown in Figure 8 describes how this process takes place. First, on the left hand side of Figure 8, the box labeled 'pictures' represents the presentation of the animation. The pictures from the animation impinge on the learner's eyes, producing a sensory image that does not require any effort on the part of the learner. This is when active processing begins. During this time, the learner must determine which images are important for making sense out of the animation (Mayer, 2001). The parts of the animation attended to by the learner will form a visual image base in the learner's working memory. The images assigned to the visual image base are organized into an understandable structure – a mental model of what is being presented. Because of the limited processing capacity of the cognitive system, the learner only has the ability to pay attention and select a part of a complex visual representation being presented. Since the learner must focus only on part of the incoming stimulus, they must judge which are the relevant parts of the animation that would allow him or her to make sense of the presentation (Mayer, 2001).

The next sections introduce Chapters 2 and 3 and describe the research questions for the studies presented in these chapters. In Chapters 2 and 3, I describe the research I performed to study the effect of adding extraneous visual images to or removing relevant visual images from an animation of an oxidation-reduction reaction on students' conceptual understanding of the processes involved in this type of reaction. Chapter 4 summarizes my findings and provides limitations as well as future studies that could elaborate on the findings from this dissertation.

Chapter 2 – Showing or Omitting Water Molecules

The first research article (Chapter 2) consists of two studies, the visual complexity study (performed by Dr. Deborah P. Rosenthal as part of her Doctor of Arts dissertation at MTSU) and the water molecules study (performed by me as part of this Doctor of Philosophy dissertation at MTSU). The water molecules study compared students' explanations of the oxidation-reduction process after viewing either the more simplified animation used in the Rosenthal and Sanger studies (Figure 9a) that did not show water molecules or an animation of the same reaction that only differed from the previous animation by showing water molecules (Figure 9b).

The research questions I examined for the water molecules study are: (1) How does viewing a computer animation that shows or omits water molecules affect students' conceptual understanding of the oxidation-reduction process depicted in these animations? (2) After viewing both animations, what do students think are the important differences between how the two animations depict visual information regarding the oxidation-reduction process? (3) After viewing both animations, which animations do the students believe should be used in the future to teach students about the oxidation-reduction reaction depicted in these animations?



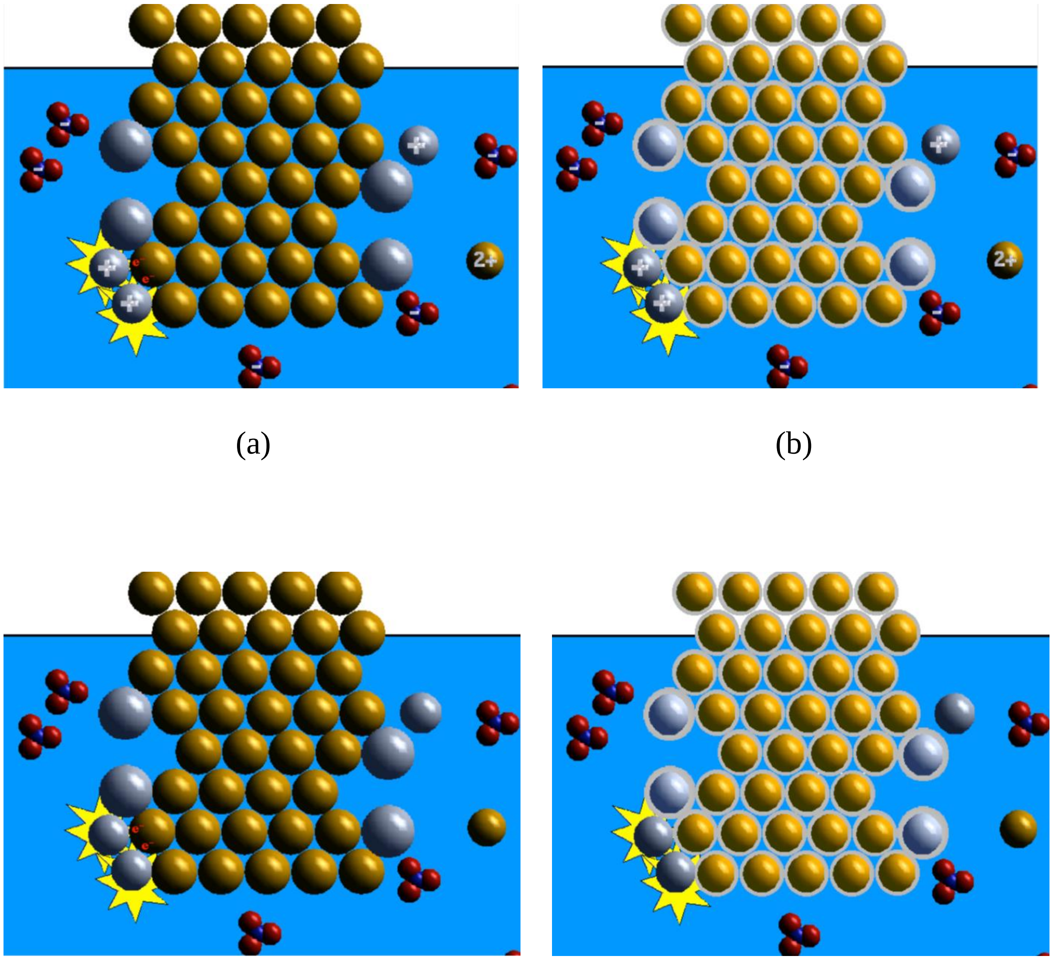
(a) (b)

Figure 9. Screen shots of the two animations used in the water molecules study study. The animation created by Sanger are (a) the water omitted animation and (b) the water shown animation. Adapted from “Two Studies Comparing Students’ Explanations of an Oxidation-Reduction Reaction After Viewing a Single Computer Animation: The Effect of Varying the Complexity of Visual Images and Depicting Water Molecules,” by M. H., Cole, D. P. Rosenthal & M. J. Sanger, 2019, *Chemistry Education Research and Practice*, *20*, pp. 742, 749.

Chapter 3 – The Ion Charges/Transferred Electrons Study

The second research paper compared students’ explanations after viewing one of four animations depicting the ion charges and the transferred electrons differently. In the four animations, the ion charges for the silver, copper(II), and nitrate ions were either labeled on the ions (Figure 10a and 10b) or omitted from the animation (Figure 10c and 10d). Similarly, the animations in Figures 10a and 10c depicted the electrons transferred from the silver ions to the copper atoms as red ‘e^-’ particles while the animations in Figures 10b and 10d depicted the transferred electrons as a silvery “halo” surrounding the outside of the metal atoms.

The research questions I examined for the ion charges/transferred electrons study are: (1) Does labeling or omitting the charges of all ions in the animation (silver, copper(II), nitrate ions) affect students' ability to explain the oxidation-reduction process?



(a) (b)

(c) (d)

Figure 10. Screen shots from the four animations used in the ion charges/transferred electrons study: (a) The animation with ion charges and with transferred electrons as particles, WC_EP, (b) the animation with ion charges and the transferred electrons as halos, WC_EH, (c) the animation with no ion charges and with transferred electrons as particles, NC_EP, and (d) the animation with no ion charges and with transferred electrons as halos, NC_EH.

(2) Does depicting the electrons being transferred from copper atoms to silver ions as ‘e–’ particles or as a fuzzy cloud or halo affect students’ ability to explain the oxidation-reduction processes? (3) Is there an interaction effect between the way the ion charges and the transferred electrons are depicted on students’ explanations of the oxidation-reduction process?

CHAPTER 2: TWO STUDIES COMPARING STUDENTS' EXPLANATIONS OF AN OXIDATION-REDUCTION REACTION AFTER VIEWING A SINGLE COMPUTER ANIMATION: THE EFFECT OF VARYING THE COMPLEXITY OF VISUAL IMAGES AND DEPICTING WATER MOLECULES

Martin H. Cole

Physical Sciences Department, Holyoke Community College, Holyoke, MA 01040

Deborah P. Rosenthal

Physical Science Department, Bakersfield College, Bakersfield, CA 93305

Michael J. Sanger

Department of Chemistry, Middle Tennessee State University, Murfreesboro, TN 37132

Abstract

This paper describes two studies comparing students' explanations of an oxidation-reduction reaction after viewing the chemical demonstration and one of two different particulate-level computer animations. In the first study, the two animations differed primarily in the complexity of the visual images. Students viewing the more simplified animation provided better explanations identifying water and nitrate ions in the animations, the absence of ion pairs, the correct ratios of silver to nitrate ions and silver ions to copper atoms, the electron transfer process, size changes in the atoms and ions as the reaction occurred, the source of blue color in solution, and the driving force for the reaction. Students viewing the more simplified animation also wrote more correct balanced chemical equations for the reaction compared to students viewing the more complex animation. Students in the first study also noted that the more simplified animation did not depict extraneous information (camera angle changes, the overabundance of water molecules), and did depict relevant information (atom and ion charges, the number of electrons transferred, the source of the blue color). In the second study, the two animations differed only by whether water molecules were shown or omitted from the animation. Students' explanations for most concepts were similar for these two groups of students; however, students viewing the animation with water molecules omitted were better able to identify nitrate ions in the animation. The only difference the students in the second study noticed between the two animations is the presence or absence of water molecules, but these student did not agree as to whether showing or omitting water molecules was more beneficial. The results of the two studies together suggest that showing or omitting water molecules in the animations had a limited effect on students' explanations of the oxidation-reduction process.

Keywords

Audience: High School/Introductory Chemistry, First-Year Undergraduate/General

Domain: Chemical Education Research

Pedagogy: Misconceptions/Discrepant Events, Multimedia-Based Learning

Topic: Aqueous Solution Chemistry; Electrochemistry; Oxidation/Reduction

Introduction

Electrochemistry and its related topics can be very difficult for students to understand, and several researchers have identified students' misconceptions and difficulties related to galvanic and electrolytic cells (Garnett & Treagust, 1992b; Loh & Subramaniam, 2018; Sanger & Greenbowe, 1997a; Schmidt, Marohn, & Harrison, 2007;

Supasorn, 2015; Tsaparlis, 2018), oxidation-reduction reactions (Brandriet & Bretz, 2014; De Jong, Acampo, & Verdonk, 1995; Garnett & Treagust, 1992a; Lu, Bi, & Lui, 2018, 2019; Rosenthal & Sanger, 2012), and the electrical conductivity of aqueous solutions (Lu & Bi, 2016; Lu et al., 2019; Nyachwaya, J. R., 2016; Sanger & Greenbowe, 1997b). One reason why these concepts may be difficult for students to understand is that explanations of these processes require students to focus their attention on the dynamic processes involving the movement of electrons and other charged particles (Loh & Subramaniam, 2018; Rosenthal & Sanger, 2012; Tsaparlis, 2018). Previous research studies have also shown that the use of computer animations or simulations at the particulate level can help students improve their conceptual understanding of these electrochemistry concepts (Kelly, Akaygun, Hansen, & Villalta-Cerdas, 2017; Osman & Lee, 2014; Sanger & Greenbowe, 2000; Talib, Matthews, & Secombe, 2005; Yang, Greenbowe, & Tibell, 2004).

Several chemical education researchers have demonstrated that the use of computer animations depicting chemical phenomena at the particulate level can improve students' conceptual understanding of these phenomena on topics other than electrochemistry, especially their particulate-level understanding (Antonoglou, Charistos, & Sigalas, 2011; Ardac & Akaygun, 2004; Gregorious, Santos, Dano, & Guiterrez, 2010a; Gregorious, Santos, Dano, & Guiterrez, 2010b; Kelly & Jones, 2007; Kelly & Jones, 2008; Kelly, Phelps, & Sanger, 2004; Russell, et al., 1997; Ryoo, Bedell, & Swearingen, 2018; Sanger, 2009; Sanger, Brecheisen, & Hynek, 2001; Sanger, Phelps, & Fienhold, 2000; Tasker & Dalton, 2006; Williamson & Abraham, 1995; Williamson, et al., 2012). In addition, research studies have shown that learning interventions using computer animations/simulations of chemical phenomena at the particulate level improved students' spatial abilities (Al-Balushi, Al-Musawi, & Ambusaidi, 2017; Williamson et al., 2013).

In 1998, Roy Tasker described his work on the VisChem Project, a series of three-dimensional computer animations depicting the particulate behavior of atoms, molecules, and ions (Tasker, 1998). The animations created and subsequently disseminated by this group used an evidence-based, multimedia information-processing model to probe students' mental models regarding the particulate behavior of the chemicals before showing them these animations. Tasker (1998, 2005) also pointed out (with some pretty egregious examples) that there were several other chemistry computer animations available at the time that incorrectly depicted the particulate behavior of atoms, molecules, and ions, and cautioned that the use of these incorrect animations could foster or even generate student misconceptions. However, no research studies were described in which students' interpretations of these two types of animations were directly analyzed and compared with respect to the formation of correct or incorrect conceptions.

Kelly and Jones (2008) asked students to describe the process of dissolving solid sodium chloride in water at the particulate level after viewing a chemical demonstration, and then again after viewing two different particulate-level computer animations depicting the process. Both animations were deemed to have good production quality, correct content, and good illustrations of key features of the dissolving process. One of these animations (created by VisChem) focused on the dynamics and energetics of the dissolving process, while the other animation (created by Prentice Hall) focused on the structural features of the dissolving process. Although Kelly and Jones did not provide a detailed comparison of the students' responses after viewing the two different animations, they did note that students viewing the Prentice Hall animation made changes to their self-generated solution pictures while those viewing the VisChem animation made changes to their conceptions of the dissolving process. In general, the authors found that the combination of animations led to improved (but not perfectly correct) particulate-level explanations of the dissolving process in the main areas of structure and function. However, incorrect conceptions remained and students often demonstrated difficulty incorporating the depictions shown in the animations into their mental models.

Kelly, Akaygun, Hansen, and Villalta-Cerdas (2017) asked students to compare two different animations of the same oxidation-reduction reaction of silver nitrate and copper metal: One of them was created to depict the correct electron transfer mechanism while the other was purposefully animated to be inaccurate, depicting molecules of silver nitrate reacting with the copper metal and the nitrates and one copper ion leaving as a copper(II) nitrate molecule. Students created particulate-level drawings and were asked to explain their conceptions of the reaction during interviews. This research study showed that even though most students identified the scientifically accurate animation as being the more correct animation, about half of the students revised their drawings and conceptual explanations of the process to fit the inaccurate animation; fewer changed their drawings/conceptions to match the more complex but more accurate animation. In addition, the vast majority of students thought that both animations were correct and would be useful for understanding the oxidation-reduction process, showing a general inability to determine whether the animations were scientifically correct or not. It should be noted that the more accurate animation used by these researchers is the same animation we used as the more complex animation in this paper and other publications by Rosenthal and Sanger (2012, 2013a, 2013b). This animation was designed by Roy Tasker for the *VisChem* Project. The research described in this paper is also different from the work of Kelly *et al.* (2017) in that all animations used in this paper were designed and animated to be scientifically accurate.

Rosenthal and Sanger (2012) asked students to view the non-narrated versions of two different animations of the same copper metal-silver nitrate oxidation-reduction reaction and to explain their understanding of the oxidation-reduction reaction based on their interpretation of these animations. The goal of this study was to identify the common misconceptions exhibited by students regarding the oxidation-reduction process and the difficulty some students had in correctly interpreting the visual images depicted in both animations. Many of the common errors found in this study (misidentifying the depicted water molecules and nitrate ions, predicting incorrect ion charges, incorrect silver to nitrate ion and silver to copper ratios, etc.) served as the basis for comparing students' conceptual understanding of the oxidation-reduction process after viewing the two animations in Rosenthal and Sanger's subsequent studies (2013a, 2013b), including this paper.

Using the misconceptions and misinterpretations identified in their first study, Rosenthal and Sanger (2013a) compared how the order of viewing the two non-narrated animations affected the participants’ particulate-level explanations of the oxidation-reduction reaction. The results of this study showed that participants who viewed the more complex animation followed by the more simplified animation gave better explanations of the oxidation-reduction process than the participants who viewed the more simplified animation followed by the more complex animation. As one student explained “the [more complex] one would get their attention and get them interested and get them wondering, and then the [more simplified] one would break it down.” (Rosenthal & Sanger, 2013a, p. 335). A recent study (Chen, Schneps, & Sonnert, 2016) comparing students’ learning gains from simulations using a simplified versus a more complex (scale-realistic) astronomical model of planetary distances showed that students had better conceptual gains for scale-neutral questions when using the more complex simulation followed by the more simplified simulation than when using the more simplified simulation followed by the more complex model. These researchers hypothesized that the attractiveness of the simple model may prevent further learning from the more complex model. In a subsequent study, Rosenthal and Sanger (2013b) examined how viewing one of the animations affected the students’ ensuing explanations of the other animation. Viewing the more complex animation before viewing the more simplified animation had no significant impact on students’ explanations of the more simplified animation. Viewing the more simplified animation before viewing the more complex animation, however, improved students’ explanations of the more complex animation. The researchers hypothesized the more simplified animation provided more iconic information that helped the students interpret the symbolic information in the more complex animation. When students viewed the more simplified animation followed by the more complex animation it impaired their ability to explain the source of the blue color in the solution. Rosenthal and Sanger (2013b) felt the viewers of the more complex animation expected the color change depicted in the more simplified animation to be in the more complex one and became confused when that didn't happen.

Research Questions

Even though our research group has made several comparisons of students' responses after viewing the more simplified or more complex animations, we have yet to fully describe a direct comparison of students' responses after viewing a *single* animation. The goal of first study in this paper is to describe the differences in students' conceptual understanding of this oxidation-reduction process after viewing either the more simplified or the more complex animation used in previous studies (Rosenthal and Sanger, 2012, 2013a, 2013b) and the important differences the students perceived between the attributes of these two animations that have many different features, but differ primarily in the visual complexity depicted in the animations.

Research Question 1: How does viewing a computer animation with differing levels of visual complexity affect students' conceptual understanding of the oxidation-reduction process depicted in these animations?

Research Question 2: After viewing both animations, what do students think are the important differences between how the two animations depict visual information regarding the oxidation-reduction process?

The results of the first study (and our previous research investigations) found significant differences in the way students interpreted the two particulate-level animations because these animations depicted so much information in very different ways, it was difficult to attribute which of these many differences were responsible for the differences in the students' responses. The impetus for the second study described in this paper was to create two different animations that differ only by a single variable (showing or omitting the potentially distracting water molecules in the animation) and to determine whether this single variable will affect students' particulate-level explanations of the oxidation-reduction process. Participants in this study were also asked to describe the important differences they perceived between the attributes of the two animations.

Research Question 3: How does viewing a computer animation that shows or omits water molecules affect students' conceptual understanding of the oxidation-reduction process depicted in these animations?

Research Question 4: After viewing both animations, what do students think are the important differences between how the two animations depict visual information regarding the oxidation-reduction process?

Students in both studies were asked, after viewing both animations in their respective studies, which of the two animations (or combination of the two) was helpful in learning about oxidation-reduction reactions, and which animations should be shown to future students to help them learn this information. The student responses regarding which animations should be used in the future were compared.

Research Question 5: After viewing both animations, which animations do the students believe should be used in the future to teach students about the oxidation-reduction reaction depicted in these animations?

Theoretical Framework

Underlying the theoretical framework of this study is the idea that there are three distinct, but related representations used by chemists to describe chemical reactions and other phenomena (Gilbert & Treagust, 2009; Johnstone, 2006, 2010; Talanquer, 2011; Tasker, 2005). The macroscopic representation describes qualitative observations made by chemists using their five senses while the particulate representation describes the properties and interactions of atoms, molecules, and ions. Symbols (numbers, chemical symbols, chemical formulas, balanced equations, etc.), the basis of the third representation used by chemists, represent more abstract concepts. One's ability to transform one form of representation to another is described as *representational competence* (Sanger, 2009), and this skill is critically important if students are to understand many complex chemical phenomena (Thomas, 2017). Assisting students in the development of representational competence is the reason why many particulate-level computer animations are used in the chemistry classroom (Suits & Sanger, 2013).

The explanation for the effectiveness of computer animations as educational tools comes from Mayer's cognitive theory of multimedia learning (Mayer, 2009). This theory was adapted by Mayer from Paivio's dual-coding theory (Pavio, 1986) and Baddeley's model of working memory (Baddeley, 1986). Mayer's cognitive theory of multimedia learning posits that learners have two separate cognitive channels used for processing visual (pictorial) and auditory (verbal) information, that learners have limited processing capabilities for each channel, and that learners are actively engaged in learning by attending to relevant information, organizing information into their mental schema, and integrating this new knowledge with their pre-existing knowledge. Mayer's theory also incorporates cognitive load theory (Sweller, 1994; Sweller & Chandler,1994), which states that if the cognitive load of a learning event exceeds the limits of the learner's working memory, then learning with be negatively impacted. Although intrinsic cognitive load is based on the content to be learned, extraneous cognitive load is a function of how the instructional lesson is presented and any load imposed on the lesson based on the instructional design of the lesson wastes cognitive resources without improving learning (Lee, Plass, & Homer, 2006). Although Mayer's theory does not apply solely to computer animations (i.e., it is valid for static pictures as well), it is certainly relevant to animations.

Several researchers have published summaries or meta-analyses on the effectiveness of computer animations. Sanger (2009) summarised several chemistry-specific education research studies involving computer animations and found that animations can be more effective than no additional instruction, traditional instruction involving no static pictures, and instruction involving static pictures similar to the animations. In addition, Sanger noted that animations can provide instructors with a way to introduce the particulate level of chemistry to students in the classroom, but they can also cause pedagogical problems if students misinterpret the visual images used in these animations. Höffler and Leutner (2007) performed a meta-analysis comparing the instructional effectiveness of computer animations with limited interactivity to static pictures. They found that lessons using animations had an instructional advantage over similar lessons involving static images, and that this superiority of animations over static images also applied to animations whose depicted motions were relevant to the information to be learned (i.e., not just decorative) and whose learning goals involved declarative or problem-solving knowledge. In a subsequent meta-analysis comparing computer animations to static pictures, Berney and Betrancourt (2016) also found that instruction involving computer animations was superior to comparable instruction involving static pictures. In addition, they found that this animation effect was present for factual and conceptual knowledge; when students were asked to remember, understand, or apply information; when the animations allowed no student control or interactivity; and when audio or no animation narrations were provided. This study also found a medium effect size (g = 0.773) for research studies specifically involving chemistry content. Both meta-analyses also noted that individual learner characteristics, such as spatial ability or prior knowledge can impact the effectiveness of instruction involving animations or static pictures.

Lowe and coworkers (Lowe, 2004; Lowe & Boucheix, 2008; Lowe, 2014) observed that the design and creation of many educational computer animations has been led more by intuition than research-based evidence, and that almost all of these animations focused on providing a time-faithful (“behaviourally realistic”) presentation of information to the learner. They also noted that existing theories related to learning with animations (e.g., Mayer, 2009) treated animations the same way they treated static pictures and focused solely on the cognitive aspects of learning. Lowe and Boucheix (2008) proposed a new model for learning with animations, the Animation Processing Model, that focuses on both the perceptual and cognitive processes used by learners and on both bottom-up (stimulus driven) and top-down (knowledge driven) contributions to information processing. This model has five hierarchical stages, although novices in the content area tend to focus on bottom-up strategies involving the first three levels. In Stage 1, novices parse the presented information and focus on creating “event units” consisting of a visual object and its associated behaviours; in Stage 2, novices form relationships between the event units from Stage 1, condensing them into more extensive dynamic “micro chunks” that are still isolated in space and time; Stage 3 involves integrating these micro chunks across space and time to create a well-structured internal characterisation of the animation. Stage 3 requires learners to have domain-specific knowledge that is needed to help structure the developing mental model, prevent learners from misinterpreting the information presented, and reduce the extent to which the learners are susceptible to irrelevant but salient perceptual cues (Lowe & Boucheix, 2008).

The differential effect on learning that can occur due to the use of more or less visually complex images in the computer animations can either be explained by the coherence principle from Mayer’s cognitive theory of multimedia learning (Mayer, 2009) or cognitive load theory (Sweller, 1994; Sweller & Chandler, 1994). Mayer’s coherence principle states that students learn more effectively when extraneous material or information is excluded from the animation. These “seductive details” (as Mayer calls them) represent information that might prove to be interesting to the learner, but does not provide any relevant information for learning the content of interest. As such, these seductive details serve to catch and divert the learner's attention away from more relevant information being presented in the animation (Garner, Gillingham, & White, 1989; Harp & Maslich, 2005 Moreno & Mayer, 2000). But what if the information presented by the more complex images in a computer animation is not extraneous and is relevant to the content to be learned? Relevant information can also overload a learner's working memory if the intrinsic cognitive load of the lesson or the extraneous cognitive load introduced by relevant but complex images in the computer animations become too high.

Lastly, the implementation and interpretation of the research studies in this paper has been informed by variation theory (Bussey, Orgill, & Crippen, 2013; Kelly, 2014). Variation theory is used to explain why different learners who experience the same instructional lesson often learn different things and at different levels. This theory focuses on which instructional features a learner pays attention to since these features and the meaning placed on them determine an individual's perception of a given learning event and the important aspects within it. Any research study informed by variation theory must examine three aspects of learning (intended, enacted, and lived objects of learning) and their relationships. The intended object of learning considers the instructor's perspective and represents what the instructor intends students to learn from the lesson. The enacted object of learning represents what actually happened during the lesson and is dictated by the interactions of the students, the instructor, and the instructional materials. The lived object of learning focuses on the student's perception of the lesson and what the student was actually able to learn from the lesson. Bussey *et al.* (2013) have modified the variation theory to include the effects of the learner's prior knowledge and skills (which affects what information students perceive and attend to, impacting the lived object of learning) and the effects of the instructional materials design (which affects how the instructional lesson is presented, impacting the enacted object of learning). Previous research on learning with animations have noted that the individual differences associated with the learner's spatial ability or prior knowledge can have a large impact on the effectiveness of learning using animations (Berney & Betrancourt, 2016, Höffler & Leutner, 2007; Lowe & Boucheix, 2008).

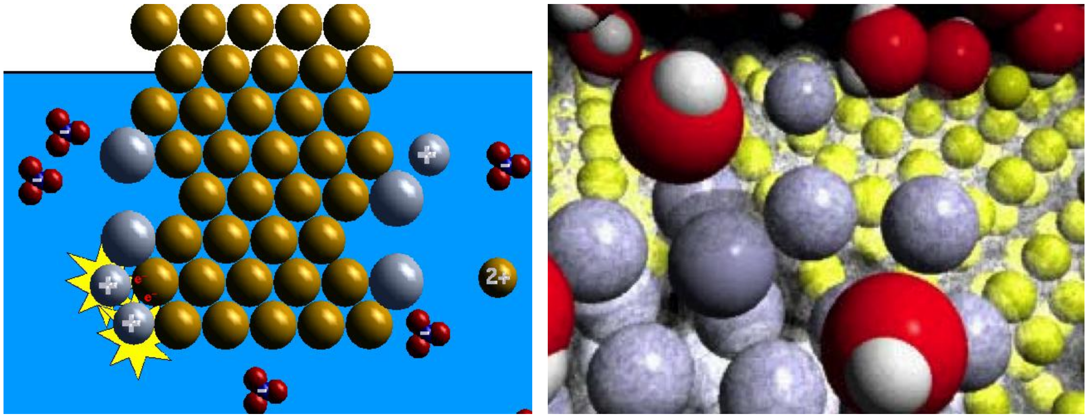
All of the animations used in these studies were created to teach the same chemistry concepts related to oxidation- reduction reactions, but use different visual images to convey this information to the learner. The intended objects of learning in both studies are represented by the content questions posed to the participants; these represent the information the researchers (as instructors) expected students to learn from viewing each of the animations. The lived objects of learning were measured by the participant's responses to these content questions and the extent to which they learned the content the researchers had intended them to learn from the animations (Research Questions 1 and 3). The enacted object of learning, which is concerned with the students' perceived differences (variations) in the lessons provided by the two different animations, was measured by asking the participants to compare the two different animations and discuss how they are different (Research Questions 2, 4, and 5). Although the differences that students deem to be important (critical features) may not be the same as those identified by the researchers or animation designers, they allow us to focus on the students' perceptions of the learning environment and what information they think is important and necessary for learning to occur.

STUDY 1: COMPARING STUDENT RESPONSES TO THE MORE SIMPLIFIED *VERSUS* THE MORE COMPLEX ANIMATION

Visual Complexity Study – Methods

Participants. The participants in this study came from two second-semester general chemistry courses taught by the same experienced college-level chemistry instructor (39% male/61% female; average age = 23.1) who did not use any kind of animations in this course. The students were contacted in the lecture after receiving classroom instruction on oxidation-reduction reactions and electrochemistry and were asked to volunteer to be interviewed as part of a research study; the instructor agreed to give each volunteer a small amount of bonus points for participating in the study (10 bonus points in a class with a total of 1000 points). Fifty-five of these students volunteered and participated in this study. These semi-structured interviews lasted from 40-70 minutes and were digitally recorded and transcribed by the second author. This research study was approved by the MTSU Institutional Review Board (protocol # 08-138).

Computer animations. A screen shot of the more simplified (MS) animation, which was created by the third author, is shown in Figure 11a. In this 2-D animation, the solid copper metal is represented by tightly packed and organized golden spheres. Silver ions are depicted as silver spheres with a positive (+) charge in the middle of the sphere floating in the aqueous solution represented by a blue background. Nitrate ions appear as triangular shaped clusters, consisting of one blue nitrogen sphere surrounded by three red oxygen spheres and a negative (-) charge, floating in the blue background also. When two positively charged silver spheres strike the same neutral copper sphere, a flash appears behind the two silver spheres. When these three objects come in contact, two red electrons (e^-) appear on the copper sphere and each of them moves from the copper sphere to one of the two silver spheres. When the transfer occurs the golden sphere becomes smaller and positively charged (2+) and each silver sphere becomes larger and neutral (no charge). The two neutral silver spheres attach to the cluster of golden spheres while the positively charged copper sphere moves into the blue background. This process occurs four times throughout the animation; each time, the blue background changes to a darker blue color.



(a) (b)

Figure 11. Screen shots for the more simplified (a) and more complex (b) animations used in Study 1. The animation in Figure 1a is also used as the water-omitted animation in Study 2.

The blue/red clusters move throughout the area of the blue background and collide with several other objects, but do not change during the animation.

Figure 11b provides a screen shot of the more complex (MC) animation, which was created by Roy Tasker as part of the VisChem project (Tasker & Dalton, 2006) and used with his permission. The animation contains several yellow spheres in a 3-D pattern in front of a black background representing the copper metal. In between and surrounding each of the yellow spheres (copper nucleus and core electrons) is a light gray “fuzziness” (valence electrons). The cluster of yellow/light gray spheres is surrounded by several red spheres with two white spheres attached to them (water molecules). Among the red/white shapes are a few gray spheres (silver ions). Occasionally, a cluster with a blue sphere surrounded by three red spheres (nitrate ions) appears. During the animation, a gray sphere moves towards the yellow /light gray cluster.
When they touch, a transparent light gray sphere encompasses the gray sphere (electron transfer) and the gray/light gray sphere stays attached to the yellow /light gray cluster. At another place on the yellow /light gray cluster, a yellow sphere loses its light gray “fuzziness” and leaves the yellow/light gray cluster, mixing among the red/white shapes. For every yellow sphere leaving the cluster, two gray spheres attach to the cluster.

Interview protocol. The interview questions (Figure 12) were developed from a list of conceptual and propositional knowledge statements created by Rosenthal and Sanger (2012). Semi-structured interviews were chosen to allow participants and researchers to clarify and elaborate on ideas as they developed throughout the interview process. The interviews consisted of three parts.

Part 1: Questions asked after students had viewed the reaction of the aqueous silver nitrate and solid copper metal.

1. How do you know that a chemical reaction is occurring?
2. What substances are present before the reaction? Describe these substances at the particulate level. If you could "see" the atoms and molecules, what would they look like?
3. What are the products of the chemical reaction?
4. What is the function of each substance in the chemical reaction?
5. Where does the chemical reaction occur?
6. Why does the chemical reaction occur?
7. Write the balanced equation for the chemical reaction.

Part 2: Questions asked after students had viewed the first computer animation depicting aqueous silver nitrate and solid copper metal.

8. Have any of your answers changed for the appearance of the substances?
9. Have any of your answers changed for the reactants of the chemical reaction?
10. Have any of your answers changed for the products of the chemical reaction?
11. Does the animation change where you think the chemical reaction occurs?
12. Does the animation change why you think the chemical reaction occurs?
13. Write a balanced equation for the chemical reaction.
14. Does the animation help you understand the chemical reaction? If so, how?

Part 3: Questions asked after students had viewed the second computer animation involving aqueous silver nitrate and solid copper metal.

15. Have any of your answers changed for the appearance of the substance?
16. Have any of your answers changed for the reactants of the chemical reaction?
17. Have any of your answers changed for the products of the chemical reaction?
18. Does the animation change where you think the chemical reaction occurs?
19. Does the animation change why you think the chemical reaction occurs?
20. Write a balanced equation for the chemical reaction.
21. Does the animation help you understand the chemical reaction? If so, how?

Part 4: Questions asked after students had viewed both animations.

22. What are the strengths and weaknesses of each animation?
23. Should an instructor teaching about oxidation-reduction reactions use none, one, or both of these animations?
24. If you said 'both', in which order should they be shown?

*Figure 12***.** The interview questions used during the semi-structured interviews in Study 1 (based on information presented in Rosenthal and Sanger, 2012).

First, participants observed a chemical demonstration in which solid silver nitrate was dissolved in water and then a piece of copper metal was placed in the container and allowed to react. After viewing the demonstration, students were asked to describe the reaction in the container at the particulate level. Next, students viewed a non-narrated version of one of the computer animations depicting the copper metal – silver nitrate reaction at the particulate level and were asked to explain how their answers in Part 1 changed based on viewing the animation. The students were also asked to explain how they felt the computer animation helped or hindered their understanding of the chemical reaction at the particulate level. During the next part of the interview, students watched a non-narrated version of the other animation showing the same chemical reaction at the particulate level and were asked to explain how their answers had changed based on viewing the second animation. Students were randomly assigned to view either the more simplified animation first followed by the more complex animation (*N* = 26) or the more complex animation first followed by the more simplified animation (*N* = 29). Each animation ran for about thirty seconds and the students were allowed to view each animation as many times as they wanted. Since this study was interested in how students interpreted the visual images presented in these animations, the audio narrations that accompanied the animations were disabled and the students were not given a key explaining what the objects in each animation represented.

Data analysis for research question 1. Although every student in this experiment viewed both animations, the goal of research question 1 was to compare the students’ responses after viewing a single animation. Previous studies by Rosenthal and Sanger (2013a, 2013b) compared student responses after each student viewed both animations. The statistical analyses in this study compared students’ explanations for the commonly seen misinterpretations and misconceptions from the previous study

(Rosenthal & Sanger, 2012) after viewing one of the two animations. For each concept, every student was given a score, described in more detail for each question in the results section for research question 1. These scores were first determined independently by the second and third authors, and were then compared (initial inter-rater reliability was greater than 0.80) with any discrepancies resolved by these two researchers. The scores for each question were compared using the One-Way Analysis of Variance (ANOVA) statistic with the animation type (MS or MC) as the independent variable (factor). For many of these concepts, students were also given scores for their explanations after viewing the chemical demonstration but before viewing the animation; in these cases, a One-Way Analysis of Covariance (ANCOVA) was performed using the animation type as the independent variable and the pre-animation score as the covariate.

Data analysis for research question 2. Students' thoughts about the different strengths and weaknesses of the two animations were solicited after they viewed both animations. These responses were recorded on paper and a list of common ideas (categories) regarding the two animations was tabulated and refined using the constant comparison technique by the second and third authors (Glaser & Strauss, 1967; Orgill, 2007; Phelps, 1994; Sanger & Phelps, 2007). The students' comments regarding the different advantages and disadvantages of the two animations are summarized and described below.

Visual Complexity Study – Results for Research Question 1

After viewing either the more simplified or the more complex animation, students' explanations were compared for the following concepts: Identifying water in the animation, identifying nitrate ions in the animation, recognizing the absence of ion pairs in solution, recognizing a 1:1 ratio of silver and nitrate ions, recognizing a 2:1 reacting ratio of silver ions and copper atoms, explaining the electron transfer process, recognizing size changes of the silver ion and copper atom, identifying the source of the blue colour in solution, recognizing that water is not the driving force for this reaction, and writing a balanced equation for the reaction. A summary of the statistical data for these comparisons is given in Table 1.

Table 1

Results for the Statistical Comparison of the Two Animation Types in Study 1

	Animation effect					Covariate		
Concept	*df*	*F* value	*p* value	MC scores (st. dev.)	MS scores (st. dev.)	*df*	*F* value	*p* value
Identifying water	1,53	7.660	0.008[a]	0.621[d] (0.075)	0.923[d] (0.079)	—	—	—
Identifying nitrate ions	1,53	18.162	0.000[a]	0.448[d] (0.077)	0.923[d] (0.081)	—	—	—
Absence of ion pairs	1,52	20.738	0.000[a]	0.414[d] (0.077)	0.923[d] (0.081)	1,52	0.010	0.921
1:1 silver-nitrate ratio (interviews)	1,52	43.793	0.000[a]	0.000[d] (0.064)	0.615[d] (0.067)	1,52	0.085	0.771
1:1 silver-nitrate ratio (balanced equations)	1,52	7.479	0.009[a]	0.578[d] (0.068)	0.856[d] (0.072)	1,52	18.309	0.000[b]
2:1 silver-copper ratio (interviews)[c]	—	7.416	0.000[a]	0.000[d] (0.135)	1.000[d] (0.135)	—	—	—

Table 1 (continued)

Concept	Animation effect					Covariate		
	df	*F* value	*p* value	MC scores (st. dev.)	MS scores (st. dev.)	*df*	*F* value	*p* value
2:1 silver-copper ratio (balanced equations)	1, 52	28.129	0.000[a]	0.279[d] (0.067)	0.804[d] (0.071)	1,52	15.781	0.000[b]
Electron transfer process	1, 52	251.190	0.000[a]	0.357[e] (0.117)	3.102[e] (0.124)	1,52	65.541	0.000[b]
Atom/ion size changes	1, 53	39.237	0.000[a]	0.552[f] (0.138)	1.808[f] (0.146)	—	—	—
Source of the blue colour in solution	1, 52	27.581	0.000[a]	0.797[f] (0.100)	1.573[f] (0.106)	1,52	67.760	0.000[b]
Water is not the driving force (ignoring nitrates)	1, 52	13.016	0.000[a]	0.630[d] (0.068)	0.990[d] (0.072)	1,52	0.686	0.411
Water is not the driving force (including nitrates)	1, 52	41.626	0.000[a]	0.360[d] (0.065)	0.983[d] (0.069)	1,52	2.193	0.145
Writing a balanced equation for the reaction	1, 52	9.027	0.004[a]	14.88[g] (0.680)	17.87[g] (0.719)	1,52	3.158	0.066

[a] $p < 0.05$ corresponds to a significant difference between explanations of the two animations

[b] $p < 0.05$ corresponds to a significant relationship between the dependent variable and the covariate

[c] A test of proportions (z-test) was performed due to a lack of variability in the responses from one of the student groups

[d] Maximum score 1, [e] Maximum score 4, [f] Maximum score 2, [g] Maximum score 20

The fact that several of the covariate scores are statistically significant indicates that the students' prior knowledge of oxidation-reduction reactions affected their interpretations of the animations, which is consistent with previous research showing that prior knowledge can affect learning using animations (Berney & Betrancourt, 2016; Höffler & Leutner, 2007; Lowe & Boucheix, 2008).

Identifying water in the animation. All of the 55 students in this study correctly identified the water in the chemical demonstration as the colourless liquid. The more simplified animation did not depict water molecules at the particulate level, but instead depicted water at the macroscopic level as the blue background in the animation; the more complex animation depicted water molecules as clusters of one red and two white spheres moving throughout the animation. After viewing the animations, 92% of the students viewing the more simplified animation correctly identified the water as the blue background while 62% of the students viewing the more complex animation correctly identified the red/white clusters as water molecules, $F(1, 53) = 7.660$, $p = 0.008$. Most of the students who incorrectly identified the red/white clusters in the more complex animation thought that they were nitrate ions, even when they mentioned seeing only two white spheres attached to a red sphere.

Identifying nitrate ions in the animation. All of the 55 students in this study identified the nitrate ions in the chemical demonstration as being part of the white solid (silver nitrate). Both animations depicted the nitrate ion as a cluster of one blue atom and three red atoms; the more simplified animation also had this cluster labelled with a '–' symbol, signifying the charge of the nitrate ion. After viewing the more simplified animation, 92% of the students correctly identified the nitrate ion, while 45% of the students viewing the more complex animation correctly identified the blue/red clusters as nitrate ions, $F(1, 53) = 18.162$, $p < 0.001$. Most of the students who incorrectly identified the blue/red clusters thought that they were water molecules, hydrated copper ions, or the object making the aqueous solution turn blue as the reaction occurred.

Recognizing the absence of ion pairs in solution. Many students believe that ionic compounds dissolve in water as neutral ion-pairs; this misconception has been widely documented in the chemical education literature (Boo, 1998; Butts & Smith, 1987; Kelly & Jones, 2007, 2008; Liu & Lesniak, 2006; Nyachwaya, Mohamed, & Roehrig, 2011; Smith & Metz, 1996; Smith & Nakhleh, 2011; Tien, Teichert, & Rickey, 2007). Only 8% of the students viewing the more simplified animation indicated the presence of ion-pairs in solution while 59% of the students viewing the more complex animation thought ion-pairs were present in solution ($F(1,52) = 20.738$, $p < 0.001$). After viewing the more simplified (MS) animation, many students felt confident that the silver or copper(II) ions would not be associated with the nitrate ions. However, those students who misidentified the red/white clusters in the more complex animation (MC) as nitrate ions confused the interactions of silver or copper(II) ions with water molecules as representing ion pairs in solution.

Interviewer: Is that what you thought silver nitrate would look like in the container?
MS Student: Uh, no.

Interviewer: What did you think it would look like?

MS Student: I thought the silvers and the nitrates would be connected.

MC Student: Silver came in with the reds and whites, so silver nitrate came in and then it goes to the copper… We see two things come together so it has to be copper and nitrate.

Recognizing a 1:1 ratio of silver and nitrate ions. Roughly 20% of students in both groups explicitly mentioned a 1:1 silver-to-nitrate ratio in the chemical demonstration interviews. Of the students who viewed the more simplified animation, 62% specifically mentioned this 1:1 ratio in their interviews; 0% of the students viewing the more complex animation mentioned the proper ratio, $F(1, 52) = 43.793$, $p < 0.001$. For the 38% of students viewing the more simplified animation who did not mention a 1:1 ratio, the interview transcripts showed no mention of the silver-to-nitrate ratio at all. In the group of students viewing the more complex animation, 11 students (38%) believed that there were more silver ions than nitrate ions. The more complex animation shows fewer nitrate ions compared to the silver ions (presumably since the nitrate ions are spectators and could be omitted from the more complex animation for clarity); however, this depiction does seem to have affected students' conceptual understanding of the chemical system. Another 38% of the students who viewed the more complex animation believed that there were more nitrate ions than silver ions. These students seemed to misinterpret the red/white shapes (water molecules) as nitrate ions, and as a result saw many more of these "nitrate ions" compared to silver ions.

Interviewer: [What are the] red/white things?

MC Student: I say they're nitrates.

Interviewer: Let's talk about ratios. How many silvers and how many nitrates should we have together?

MC Student: One silver, two nitrates.

Interviewer: Does it [animation] have equal amounts?

MC Student: A lot more nitrates than silvers.

It is possible that some of the students who failed to explicitly mention the 1:1 ratio still believed that the silver and nitrate ions were present in equal amounts. So, we decided to evaluate the chemical formulas for silver nitrate in their self-generated balanced equations. For the chemical demonstration part of the interview, 77% of students viewing the more simplified animation and 55% of students viewing the more complex animation wrote the formula for silver nitrate as '$AgNO_3$'. After viewing the animations, 92% of students seeing the more simplified animation and 59% of students viewing the more complex animation wrote balanced equations showing a 1:1 silver-to-nitrate ratio, $F(1, 52) = 7.479$, $p = 0.009$.

Recognizing a 2:1 reacting ratio of silver ions and copper atoms. About 23% of students viewing the more simplified animation and 0% of students viewing the more complex animation explicitly mentioned a 2:1 reacting ratio for the silver ions and the copper atoms in the chemical demonstration interviews. After viewing the animations, 100% of students viewing the more simplified animation and 0% of students viewing the more complex animation specifically mentioned this 2:1 ratio in their interviews. Because there was no variability in the responses from the more complex group (i.e., every student gave the same answers before and after viewing the animation), an

ANCOVA score could not be calculated. So, we performed a test of proportions instead, $z = 7.416$, $p < 0.001$.

The more simplified animation depicts two silver ions and one copper atom undergoing electron transfer at the same time and place while the more complex animation depicts the reduction of two silver ions and the oxidation of one copper atom as happening at different times and on different places on the copper metal surface. These results suggest that the realistic depiction of the oxidation-reduction process shown in the more complex animation confused students regarding the relative number of silver ions and copper atoms involved in the oxidation-reduction reaction. This difference could also be explained by Lowe's Animation Processing Model (Lowe and Boucheix, 2008; Lowe, 2014)—since the more simplified animation showed the silver ion-copper atom reaction happening at the same place and time in the animation, interpreting this ratio only required students to work at Stage 2, but since the more complicated animation showed this reaction happening at different times and at different spots of the copper surface, students would have to have been working at Stage 3 in order to integrate these micro chunks from Stage 2 across space and time to create a well-structured internal characterisation of this ratio from the animation.

Some of the students viewing the more complex animation thought the reacting ratio was close to 1:1, a few thought it was close to 2:1 but weren't sure and told us they were guessing, and others thought it might be 3:1 or 5:1.

Interviewer: Can you tell the relative amounts? How many coppers or silvers [reacting]?

MC Student: It looks like at least two silvers to one copper, at least.

Interviewer: Guess or obvious?

MC Student: Not real obvious. They show [a] cluster of silver and every once in a while a copper comes out.

Since it is possible for students to believe in the 2:1 reacting ratio without explicitly mentioning it, we evaluated the reacting ratios in their self-generated balanced equations. For the chemical demonstration part of the interview, 23% of students viewing the more simplified animation and 14% of students viewing the more complex animation wrote a 2:1 reacting ratio for silver nitrate and copper metal. After viewing the animations, 85% of students viewing the more simplified animation and 24% of students viewing the more complex animation showed a 2:1 reacting ratio for silver nitrate and copper metal, $F(1, 52) = 28.129$, $p < 0.001$.

Explaining the electron transfer process. Students' scores for the electron transfer process were based on a four-point scale. One point was given to each student for the following ideas: (1) Silver ions gain electrons as part of the reaction, (2) each silver ion gains one electron, (3) copper atoms lose electrons as part of the reaction, and (4) each copper atom loses two electrons. Both pre- and post-animation explanations were scored with the pre-animation scores being used as the covariate. The adjusted least squares means (corrected for the students' pre-animations scores by the ANCOVA calculation) were 3.1 out of 4 for the students viewing the more simplified animation and 0.4 out of 4 for the students viewing the more complex animation ($F(1, 52) = 251.190$, $p < 0.001$). Students viewing the more complex animation were more likely to provide descriptions of the reaction that did not mention electron transfer from copper to silver, and very few of them discussed the number of electrons gained or lost as a result of the reaction. Many students viewing the more simplified animation, on the other hand, provided explanations including all four ideas.

MC Student: The water is taking away the copper ion to make copper nitrate, and silver just stays solid. Silver is getting dropped off; silver is bundling up together. If silver is getting compacted, it must be solid. Copper is attracting the silver and once the silver is compact, the copper is taken away by the water and nitrogen [nitrate] is floating around too so that makes copper nitrate. It looks like the silver nitrate is trading out to be copper nitrate. So it would be copper nitrate and silver solid.

MS Student: You see two silver atoms react with the copper, and one copper is released that has a +2 charge. So that must mean that two electrons were donated from the copper, one to each silver.

It appears that explicitly showing the number of electrons being transferred and the charges on the atoms and the ions, both before and after the reaction, helped students better understand the electron transfer process.

Recognizing size changes for the silver ion and copper atom. Each student was given one point for indicating that the silver ion would become larger after gaining an electron and one point for indicating that the copper atom would become smaller after losing electrons. The size change of the silver ions and copper atoms was not mentioned by any student during the chemical demonstration interviews. Therefore we did not use these scores as a covariate in the ANOVA analysis. Students had a mean score of 1.8 out of 2 after viewing the more simplified animation and 0.6 out of 2 after viewing the more complex animation, $F(1, 52) = 39.237$, $p < 0.001$. The more simplified animation explicitly showed these size changes by making the silver atoms larger than the silver ions and by making the copper ions smaller than the copper atoms. However, the more complex animation depicted the nucleus and core electrons of the copper and silver ions as a solid sphere and depicted the copper and silver atoms using solid spheres surround by a light grey fuzzy sphere (valence electrons). Several students viewing the more complex animation expressed confusion regarding whether the silver ions or copper atoms changed size as a result of the oxidation-reduction reaction.

Interviewer: Anything happen to the size [of the silver ion when it attached to the copper surface]?

MC Student: Maybe, if you count the almost transparent casing, but it is not real clear… but it could have gotten bigger.

Interviewer: Yes or no?

MC Student: I didn't see it get bigger.

Identifying the source of the blue colour in solution. Students were given two points for stating that the copper(II) ion is responsible for the blue colour in solution, one point for stating that copper(II) nitrate or the combination of copper and nitrate ions caused the blue colour, and zero points for any other answers. The adjusted least squares means (corrected for the students' pre-animation scores) were 1.6 out of 2 for the students viewing the more simplified animation and 0.8 out of 2 for the students viewing the more complex animation ($F(1, 52) = 27.581$, $p < 0.001$). The more simplified animation showed the light blue background representing the water turning darker blue after each oxidation-reduction event; the more complex animation did not depict the solution colour or any changes to its colour. Students viewing the more complex animation were more likely to suggest that a cluster of copper and nitrate ions made the solution blue, and some of them stated that the blue atom in the red/blue cluster represented the solution turning blue. It is unfortunate that the solution colour and the symbol for nitrogen were both blue, as this led to student confusion. In the following student quote, the student believed that the combination of copper and nitrate ions made the solution blue (based on a misrepresentation of the red/white clusters as nitrate ions) coupled with the implication that the blue atom in the red/blue cluster represents the blue colour of the solution.

MC Student: I think the nitrate and the copper bonds together is causing the blue colour to form, [be]cause if you look at silver and nitrate [red/white cluster], nothing is formed until we switch it and you have copper and nitrate. That still leaves the question, what is that blue thing? I think a foreign object…

Interviewer: Does the animation show why the solution turns blue?

MC Student: No, [be]cause you only saw that one molecule with the blue in it. You did not see how it was formed. It just floated by. Hi, Bye.

Recognizing that water is not the driving force of the reaction. Tasker and Dalton (2006) reported that some students misinterpreted the motions of water molecules in the more complex animation as suggesting that water molecules are driving the reaction to occur by pushing the silver ions to the copper metal surface and pulling the copper ions away from the copper surface. Before viewing the animations, 19% viewing the more simplified animation and 7% viewing the more complex animation suggested that water was driving the reaction to occur. After viewing the animations, 0% viewing the more simplified animation and 38% viewing the more complex animation suggested that the water molecules were forcing the reaction to occur ($F(1, 52) = 13.016$, $p = < 0.001$). If we include the number of students mistaking the red/white clusters as nitrate ions and then suggesting that the nitrate ions were driving the reaction, the percentages of incorrect responses change to 0% for those viewing the more simplified animation and 66% for those viewing the more complex animation ($F(1, 52) = 41.626$, $p < 0.001$). Students viewing the more complex animation provided comments suggesting that the water molecules (or the “nitrate ions”) were actively involved in causing the reaction to occur, which is consistent with the findings from the Tasker and Dalton study (2006).

MC Student: It [animation] makes it look like the water is doing everything. Causing the reaction – bringing silver to copper.

MC Student: Now the reaction is occurring… Now, the nitrates [red/white clusters] go for the copper. We started with copper solid. Nitrates are coming in, taking them [points to copper ions] and stacking them [points to silver atoms] up.

Writing a balanced equation for the reaction. At the end of the interviews involving the chemical demonstration and the animation, students were asked to write a balanced chemical equation for the reaction occurring between aqueous silver nitrate and copper metal. The student-generated equations were given a score of 20 based on a list of 20 items that should appear in the equation (including chemical formulas, charges, states of matter, stoichiometric ratios, and atom and charge balance). The student scores for the chemical demonstration interview were used as a covariate. Pre-animation mean scores were 15.6 out of 20 for those viewing the more simplified animation and 14.5 out of 20 for those viewing the more complex animation. After viewing the animations, the adjusted least square means were 17.9 out of 20 for those viewing the more simplified animation and 14.9 out of 20 for those viewing the more complex animation ($F(1, 52) = 9.027$, $p = 0.004$). Students viewing the more simplified animation were more likely to write the correct formula for copper(II) nitrate and were more likely to have a balanced equation showing a 2:1 stiochiometric ratio for the reactants and for the products than those viewing the more complex animation.

Visual Complexity Study – Results for Research Question 2

After viewing both animations, students were asked to provide a list of strengths and weaknesses for the two animations, and how the animations were different from each other. These responses were compiled and categorized to create list of common ideas expressed (in one form or another) by at least 10% of the total population. These common ideas include: The usefulness of the computer animations, the complexity of the computer animations, depicting water molecules, showing the charges of the atoms and ions, showing the electrons as particles, and recognizing the source of the blue colour in solution.

The usefulness of the computer animations. Fourteen of the 55 students (25%) commented that they found the computer animations to be very helpful in understanding the copper metal-aqueous silver nitrate reaction at the particulate level, and several stated that they felt they would be doing better in their chemistry classes if they had more opportunities to see computer animations in their lessons. These comments don't really address how the animations were different, since they were made about both of the animations used in this study. One student also commented that even though the more complex animation confused her, she felt that it would force her to think more deeply about the chemical reaction.

MS Student: It helped give an idea of what is going on at the atomic level… it is hard to imagine what is going on, even though she [our instructor] told us but if she had shown this, it would be easier to remember. But I have never been in chemistry class where any animation was shown. I think that is why I have such a hard time with even simple things like writing equations because you can imagine a periodic table all day long, but I can't imagine what is going on [at the molecular level].

MS Student: If we could study all the reactions we study in chemistry with animations like that we would all be making A's.

MC Student: [The more complex animation] confused me. I think it would make me think, though. It would actually, like, challenge me to think about what's going on instead of … we are always being spoon-fed information. And … that demo actually made me, like … I seriously had to sit here and think and now you know, like, we strung it all together … I am definitely going to remember this tomorrow. I am not going to forget it when I walk out that door.

The complexity of the computer animations. Although no students made any comments about the complexity of Sanger's animation, several students commented about the complexity of Tasker's animation. It was these students' comments that led us to describe Sanger's animation as "more simplified" and Tasker's animation as "more complex" in our research studies. Eight students (15%) suggested that Tasker's animation was hard to interpret or busy, four students (7%) said that it showed lots of information but did not explain it, and six students (11%) recommended that the animation include narration to explain the chemical reaction. It should be noted that the audio portion of this animation that explained the chemical reaction was turned off for this study.

MC Student: It is very attractive, but swoopy and moving around and too hard to follow, with too much stuff going on.

MC Student: It showed what was happening, but did not explain it.

MC Student: …this 3D one might be more helpful with commentary or someone narrating it, explaining, because it is obviously more involved and accurate because it shows the Brownian motion of the copper – all the atoms moving because it shows the atoms moving, [be]cause they are not at absolute zero and it shows the electron clouds. But the problem is, it shows it all at once and the camera never stops moving and it is hard to pick out the relevant information… [be]cause I don't really feel like I am gaining anything by the camera orbiting around, but on the other hand you kind of have to zoom in on parts.

Five students (9%) mentioned that Tasker’s animation was difficult to follow because the camera angle was constantly changing throughout the animation, and they also implied that the combination of changing camera angles and the number of objects being depicted on the screen overloaded their thought processes.

MC Student: It is a nice animation to watch. Then it moves.

Interviewer: Oh, the camera moves?

MC Student: Yeah, the viewing angle is weird. It looks like the camera is trying to get what is happening over the entire surface of the copper wire in as short of time as possible and if it would focus on one area, you would see copper is leaving and silver is coming, but it is trying to get too much …

Depicting water molecules. The more simplified animation did not depict the water molecules and only represented water at the macroscopic level as the blue background. While two students (4%) thought that it was a strength that this animation did not show the water molecules, four students (7%) thought that it was a weakness.

MS Student: The only thing I don’t like is this one does not show the water. If you could just take this one and show water molecules in it.

MS Student: Maybe put waters [molecules in the animation], but it would be too confusing. Just make sure to say the blue background is water.

The more complex animation did depict the water molecules, showing that aqueous solutions (like silver nitrate solution in this reaction) are composed of a large number of water molecules compared to the number of ions dissolved in the water. Although eight students (15%) felt that depicting so many water molecules was a strength, eight students (15%) felt that including so many water molecules confused them. Some students who incorrectly identified the red/white clusters as nitrate ions also claimed that there were too many nitrate ions in the system based on the formula for silver nitrate. The identity of the red/white clusters is explained in the audio portion of Tasker's animation that was disabled as part of this study.

MC Student: They could have done with less water. It is not confusing; it is distracting… It [the solution] has a lot of water. I get that they are trying to get that across.

Interviewer: Is there anything you would do to fix that?

MC Student: Take out all the water molecules. It is a good animation for really advanced [students] if you already understand the concepts, but if it is the first time you encounter the reaction and have not talked about it, it is really confusing.

MC Student: The main thing again is that there is just seems to be a surplus of nitrate, which is not realistic in regards to the equation itself. So it skews my perception. I would presume there is a lot more nitrate needed if I had not seen the bottle with silver nitrate written on it. I might write six N-O-3 to one A-G, but it looks like 25.

Showing the charges of the atoms and ions. The most commonly reported strength of the simplified animation, mentioned by 23 of the 55 students (42%), is that it shows the charges of the atoms and ions in the system. These students recognized the importance of knowing the charges of the atoms and ions before and after the reaction in order to understand several aspects of the oxidation-reduction reaction.

MS Student: Main thing about [the animation] is the charges. It showed exactly which was gaining and losing [electrons], and the states, and the ratio.

Interviewer: What is your general feeling about the animation? Is it helpful?

MS Student: It was helpful in some parts. We got our equation right [be]cause we looked at it.

Interviewer: What part of the animation helped with the equation?

MS Student: We could not remember if the nitrate was a minus one or minus two charge.

The more complex animation does not explicitly label the charges on the atoms or ions, and six students (11%) felt that this was a definite weakness of the animation. Some of these students also felt that the lack of charges also prevented them from understanding the chemical reaction and hindered their ability to write a balanced equation for this reaction.

MC Student: I think this one makes it harder for me to understand, [be]cause… there are not charges depicted in this animation.

Interviewer: Balanced equation? Does this animation make you change your answer?

MC Student: I don't believe so. The only issue that remains is the charges. If I knew the charges of silver and copper, I would know charges of nitrate and that would change my subscripts.

Showing the electrons as particles. Fifteen students (27%) stated that the more simplified animation was helpful in understanding the electron transfer process. One of the strengths of this animation is that it showed discrete electrons ('e^-' symbols) being transferred from one copper atom to two silver ions, and these students also commented that understanding the electron transfer process also helped them understand other important concepts such as the why the atoms and ions changed sizes and why the reaction followed a 2:1 silver-copper stoichiometry.

MS Student: I liked where you can see the electrons moving. In the demonstration, you do not see the molecules moving out, so it kind of helps you understand what is going on… For me, watching the two silver hit before the copper was released with the exchange of electrons and watch it get bigger and smaller really helped me visual[ise] what is going on in the beaker.

For the more complex animation, four students (7%) felt that the depiction of the electron cloud for the valence electrons in copper metal was more realistic. However, four students (7%) also believed that the way this animation depicted the electron transfer process was vague or confusing. The student quote below shows that he recognized the realistic nature of depicting bulk copper metal using a field of electrons, and that the electron transfer process occurred because electrons were transferred from copper atoms to silver ions. However, he could not determine *how many* electrons were transferred during the oxidation-reduction process.

MC Student: It is more realistic picture, as far as showing the packing structure. Copper solids here.

Interviewer: Did it help you with any charges, or phases, or sizes?

MC Student: It showed that there was a charge change, but not what it was. There was just a white cloud. It confirms to me that we learned in class how electrons can just float everywhere, [be]cause each copper atom does not have its own cloud. The cloud surrounding the whole solid.

Recognizing the source of the blue colour in solution. Thirteen students (24%) believed that the more simplified animation was more helpful in enabling them to recognize aqueous copper(II) ions as the source of the blue colour in this solution. Some of these students also noted that the animation helped them determine that it was the copper(II) ion and not the copper(II) nitrate that caused the blue colour. None of the students mentioned this as a strength or weakness for the more complex animation.

MS Student: It also showed as copper was released, the water changed colour.

MS Student: I noticed colour change. Animation of copper not bonding to nitrate helps.

Study 2: Comparing Student Responses to the Animation Depicting Water Molecules *Versus* the Animation Omitting Water Molecules

Water Molecules Study – Methods

Participants. The participants in this study came from several first- and second-semester general chemistry courses taught by different college-level chemistry instructors (44% male/56% female; average age = 22.1). Although the participants in the only survey portion of this study did not receive any instruction using animations in their courses, the students volunteering for the interview portion of this study did receive instruction by the last author using computer animations much like those used in this study. The interview students were contacted in the lecture after receiving classroom instruction on the oxidation-reduction process and balancing simple oxidation-reduction reactions and were asked to volunteer to be interviewed as part of a research study; the instructor agreed to give each volunteer a small amount of bonus points for participating in the study (10 bonus points in a class with a total of 750 points). Fifteen of these students volunteered and participated in interviews for this study. The online survey students were contacted during their lab session after receiving classroom instruction on the oxidation-reduction process and balancing simple oxidation-reduction reactions and were asked to fill out the online survey in lieu of performing that week's experiment; the laboratory coordinator agreed to give each volunteer a score of 10/10 on the lab experiment for participating in the study (students who did not volunteer for this study performed the experiment; the typical average for laboratory experiments graded by the teaching assistants was about 9.0-9.5/10 for these classes). Fifty-seven of these students volunteered and participated in the online survey for this study. The semi-structured interviews lasted from 60-120 minutes and the online surveys lasted from 20-60 minutes; the written responses provided by both groups of students were recorded by Qualtrics (Qualtrics, Provo, UT). This research study was approved by the MTSU Institutional Review Board (protocol # 16-2040).

Computer animations. The more simplified animation from the visual complexity study (Figure 11a) was used as the animation with water molecules omitted (WO) in this study. The second animation in this study (Figure 13), in which water molecules were shown (WS) was created by the third author as a modification of the WO animation. Clusters of red spheres with two white spheres attached (water molecules) that move in the background behind the other objects (the bulk copper metal and the copper (II), silver, and nitrate ions) were added to the WO animation so that none of the blue background is now visible. All other aspects of this animation were left unchanged. The students were not given a key explaining what the objects in either animation represented.

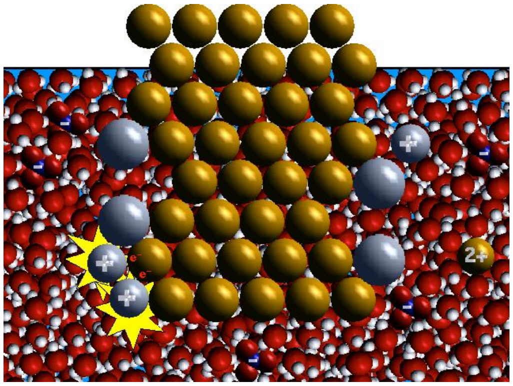


Figure 13. Screen shot for the animation showing water molecules used in Study 2.

Survey platform. For this study, an on-line survey was generated using the Qualtrics survey platform (Qualtrics, Provo, UT). This platform was utilized because it allowed the first author to embed the video demonstration and animations into the survey as well as providing the flexibility to ask multiple-choice and open-response questions. The survey questions (Figure 14) were adapted from the visual complexity study to more explicitly address important concepts that were identified in that study.

The Qualtrics platform allowed the participants to view the video demonstration and animations as many times as they wanted during the survey. The surveys were designed so that when a participant completed a section of the survey, they could not return to it. Students accessed the surveys with a web address provided by Qualtrics, using desktop computers in the third author's office for the students participating in the semi-structured interviews or in a computer lab for students in the survey group. Qualtrics collected and tabulated individual student responses into one report for later data analysis.

Interview and survey protocol. The 15 students who participated in the semi-structured interviews worked through the Qualtrics survey with the first and third authors in the room. When needed, the researchers prompted the students to clarify or elaborate on their ideas regarding the copper metal – silver nitrate oxidation-reduction reaction. These interviews were also digitally recorded and transcribed by the first author. The 57 students who participated in the survey worked through the same survey individually in a computer room and were not explicitly prompted by the researchers to clarify or elaborate on their ideas.

Part 1: Questions asked after students had viewed a video demonstration of the aqueous silver nitrate and solid copper metal reaction.

1. How do you know a chemical reaction is occurring?
2. What substances are present at the beginning of the reaction?
3. Describe these substances at the beginning of the reaction.
4. What are the products of the reaction?
5. What is the function of each of the substances in the reaction?
6. Where does the reaction occur?
7. Why does the reaction occur?
8. Write a balanced equation for the reaction you saw in the video above.

Part 2: Questions asked after students had viewed the first computer animation depicting the aqueous silver nitrate and solid copper metal reaction.

*1. Which figure in the animation represents the nitrate ion? (a) a red sphere with two white spheres at an angle, (b) a blue sphere with three red spheres in a triangular shape, (c) the nitrate ion is not shown.
*2. Are there any ions that are paired together in the animation? (a) yes, (b) no
*3. In the animation, the silver ions (a) lose electrons, (b) gain electrons, (c) have no change in electrons.
4. How many electrons does each silver ion lose or gain?
*5. In the animation, the copper atoms (a) lose electrons, (b) gain electrons, (c) have no change in electrons.
6. How many electrons does each copper atom lose or gain?
7. Why does this reaction happen?
8. In the solution, there are ___ silver ion(s) for every ___ nitrate ion(s) present.
9. In the reaction, there are ___ silver ion(s) for every ___ copper atom(s) reacting.
10. Write a balanced equation for the reaction you saw in the animation above.

Part 3: Questions asked after students had viewed the second computer animation involving aqueous silver nitrate and solid copper metal.

*1. Which figure in the animation represents the nitrate ion? (a) a red sphere with two white spheres at an angle, (b) a blue sphere with three red spheres in a triangular shape, (c) the nitrate ion is not shown.
*2. Are there any ions that are paired together in the animation? (a) yes, (b) no
*3. In the animation, the copper atoms (a) lose electrons, (b) gain electrons, (c) have no change in electrons.
4. How many electrons does each silver ion lose or gain?
*5. In the animation, the copper atoms (a) lose electrons, (b) gain electrons, (c) have no change in electrons.

Figure 14. The interview questions used during the semi-structured interviews and surveys in Study 2. The multiple-choice questions are marked with an asterisk; all other questions were open response.

6. How many electrons does each copper atom lose or gain?
7. Why does this reaction happen?
8. In the solution, there are ___ silver ion(s) for every ___ nitrate ion(s) present.
9. In the reaction, there are ___ silver ion(s) for every ___ copper atom(s) reacting.
10. Write a balanced equation for the reaction you saw in the animation above.

Part 4: Questions about which animation was more useful in understanding the oxidation-reduction process.

1. Which animation was more useful in understanding the chemical process?
2. Explain your choice in the previous question.
3. Which animation would you show in class?
4. Explain your choice in the previous question.

Figure 14 (continued).

After viewing the demonstration, one group of students (8 interview and 28 survey students) watched the 24-second non-narrated animation of the copper metal – silver nitrate reaction showing water molecules and answered the questions in Part 2 of the interview protocol in Figure 14, followed by viewing the 24-second non-narrated animation with water molecules omitted and answering the interview questions in Part 3 of the protocol. The other group of students (7 interview and 29 survey students) viewed the animations in the reverse order and answered the same questions in Parts 2 and 3 of the interview protocol. The students were allowed to watch the video demonstration and the two animations as many times as they wanted. Part 4 of the interview protocol asked students to indicate which animation they thought was more useful in understanding the oxidation-reduction process. They were also asked which animation they would show in class and if they chose both, which animation would they show first.

Data analysis for research question 3. In this study, we wanted to compare students' answers to the questions in Part 2 of Figure 14 after viewing only one of the animations (showing water molecules or omitting water molecules). Most scores were based on multiple-choice or short answer questions that required little to no interpretation. For the scores that were based on open-ended questions requiring interpretation (e.g., why the reaction occurs, write the balanced equation), the first author determined these scores and the third author confirmed these scores; any discrepancies were resolved by these researchers before any statistical analyses were performed. Analysis of these scores was accomplished using a One-Way ANOVA with the animation type as the independent variable. Additionally, we wanted to determine if, after viewing both animations, there was an order effect on students' answers depending on which animation they viewed first. A Two-Way ANOVA with the animation type and the viewing order as the independent variables was used for this analysis. For the balanced equation, student scores were compared for the chemical demonstration as well as for the animations. The statistic used for this analysis was a One-Way ANCOVA where the animation type was the independent variable and the demonstration balanced equation score was the covariate. Students in this study were also asked which animation they preferred and which animation or sequence of animations they would show in class. Students' answers to this question from Study 1 and Study 2 were compared using a Chi-Square analysis.

Water Molecules Study – Results for Research Question 3

(After Viewing One Animation)

After viewing one of the animations, students' answers to the questions in Part 2 of Figure 14 were analyzed for the following concepts: Identifying the nitrate ions in the animations, the presence of ion pairs in the solution, describing the electron transfer process, explaining the driving force, recognizing size changes of the silver ion and copper atom, recognizing a 1:1 ratio of silver and nitrate ions, recognizing a 2:1 reacting ratio of silver ions and copper atoms, and writing a balanced equation for the reaction. A summary of the statistical data for these comparisons is given in Table 2. In contrast to the visual complexity study, only one comparison was found to be significant: Identifying nitrate ions.

Table 2

Results for the Statistical Comparison After Students Had Viewed One Animation in Study 2

Concept	*df*	*F* value	*p* value
Identifying nitrate ions	1, 71	6.387	0.014[a]
Presence of ion pairs	1, 71	0.878	0.352
Electron transfer process	1, 71	0.412	0.532
Driving force	1, 71	0.000	1.000
1:1 silver/nitrate ratio	1, 71	0.000	1.000
2:1 silver/copper ratio	1, 71	0.235	0.629
Writing a balanced equation for the reaction	1, 71	3.075	0.084

[a] $p < 0.05$ corresponds to a significant difference between student responses to questions about the two animations.

Identifying nitrate ions in the animation. Students viewing the animation with water molecules shown (WS) had more difficulty identifying the nitrate ion compared to students viewing the animation with water molecules omitted (WO), $F(1, 71) = 6.387$, $p = 0.014$. For the students in the WS group, 38% incorrectly identified the nitrate ion as the red sphere with two white spheres and 49% correctly identified the nitrate ion as the blue sphere with three red spheres; for the WO group, these percentages were 22% and

78%, respectively. These results are consistent with the results seen in the visual complexity study – both studies showed that when water molecules are depicted some students will incorrectly identify them as nitrate ions. This confusion may be due to the fact that there were a lot of red-white water molecules in the animation and this visual denseness distracted the students' attention away from the red-blue nitrate clusters.

WS Student: [T]he water molecules made it more difficult to focus and find the nitrate molecules.

WS Student: With all of the water molecules, it became confusing to differentiate the ions from the water molecules. It became very busy.

The other concepts. There were no significant differences in the responses from the WO and WS groups to the following concepts: The presence of ion pairs in the solution ($F(1, 71) = 0.878$, $p = 0.352$), describing the electron transfer process ($F(1, 71) = 0.412$, $p = 0.532$), explaining the driving force ($F(1, 71) = 0.00$, $p = 1.000$), recognizing a 1:1 ratio of silver and nitrate ions ($F(1, 71) = 0.000$, $p = 1.000$, recognizing a 2:1 reacting ratio of silver ions and copper atoms ($F(1, 71) = 0.235$, $p = 0.629$), and writing a balanced equation for the reaction ($F(1, 71) = 3.075$, $p = 0.084$). This is in stark contrast to what was found in the visual complexity study, in which students' explanations for all of the concepts were better for the students viewing the more simplified animation that did not depict water molecules. While the animations in the visual complexity study differed by several aspects (water molecules shown or not, charges shown or not, electrons depicted as particles or clouds, etc.), the animations in this study differed only by the presence or absence of water molecules. The results of this study seem to indicate that it was not showing or omitting the water molecules in the visual complexity study that led to the significant differences in students' explanations of those two animations for any concept except identifying nitrate ions.

Water Molecules Study – Results for Research Question 3
(After Viewing Both Animations)

The students' answers after viewing both animations were also analyzed for the following concepts: Identifying the nitrate ions in the animations, the presence of ion pairs present in the solution, describing the electron transfer process, explaining the driving force, recognizing a 1:1 ratio of silver and nitrate ions, recognizing a 2:1 reacting ratio of silver ions and copper atoms, and writing a balanced equation for the reaction. The statistical results of these comparisons appear in Table 3. None of these comparisons were statistically significant, and this suggests that there was no order effect (i.e., the order in which students viewed the animations did not significantly change their answers); this is also in direct contrast to the order effect studies performed using the animations from the visual complexity study (Rosenthal and Sanger, 2013a, 2013b).

Misinterpreting the nitrate ions and explaining the driving force. A difference was not detected in students' explanations of the driving force of the copper metal – silver nitrate oxidation-reduction reaction after viewing both animations using an ANOVA ($F(1, 70) = 1.045$, $p = 0.310$), which compared the number of students providing a correct answer versus those providing an incorrect answer. Since the analysis of students' explanations showed that students who viewed the animation showing water molecules were more likely to incorrectly identify the red-white (water) molecules as nitrate ions, we were interested to see whether these students were more likely to claim that the nitrate ions were the driving force for this reaction.

Table 3

Results for the Statistical Comparison After Students Had Viewed Both Animations in Study 2

Concept	*df*	*F* value	*p* value
Identifying nitrate ions	1, 70	0.400	0.529
Presence of ion pairs	1, 70	0.034	0.855
Electron transfer process	1, 70	0.586	0.447
Driving force	1, 70	1.045	0.310
1:1 silver/nitrate ratio	1, 70	0.680	0.412
2:1 silver/copper ratio	1, 70	0.090	0.766
Writing a balanced equation for the reaction	1, 70	0.230	0.633

Students' explanations for the driving force question were analyzed and four major themes emerged from this analysis (Phelps, 1994). These themes for the driving force of this reaction were: Differences in the electronegativity of copper and silver was the driving force, the reaction occurs to reach stability (ΔG is the driving force), the nitrate ions were the driving force, or some other process/concept (e.g. collision theory) was the driving force. Examples of student quotes illustrating each category are listed below.

<u>Electronegativity</u>

WS Student: Because copper is more [sic] electronegative than silver.

WO Student: Silver is more electronegative than copper in this reaction, …

Stability (ΔG)

WS Student: The reaction occurs because the silver nitrate and the copper metal want to be as stable as possible.

WO Student: The two substances are trying to reach equilibrium and become as stable as possible.

Nitrate ions

WS Student: The reaction occurs because the affinity between the nitrate and the copper

ions is stronger than the affinity between the aluminum [sic] and the nitrate ions.

WO Student: It occurs because the Nitrate reacts with the Copper forming Copper Nitrate on the solid.

Other

WS Student: it is reacting magnetically to the silver nitrate.

WO Student: silver is gains [sic] an electron and copper is losing one.

Table 4 contains a summary of the students' explanations for the driving force in both groups after viewing the chemical demonstration, the first animation, and the second animation. Most of the students provided explanations in the 'Other' category. The number and identity of the students in each group providing electronegativity arguments (the “correct” answer) stayed the same throughout the experiment; these five students did not change their answers during the study, and no other students changed their answers from an incorrect answer to the correct answer as part of this study, which explains why no significant difference was seen with the ANOVA comparison of correct versus incorrect answers.

Table 4

The Number of Students Choosing the Four Driving Force Categories after Viewing the Demonstration, the First Animation, and the Second Animation in Study 2

	WS_WO students			WO_WS students		
Category	Demon stration	Animation #1	Animation #2	Demon stration	Animation #1	Animation #2
Electro negativity	3	3	3	2	2	2
Stability (ΔG)	5	5	4	8	8	6
Nitrate ions	8	4	4	5	3	7
Other	20	24	25	21	23	21

Figure 15 shows a plot of the number of students in each group claiming that the nitrate ions were the driving forces for this reaction. After viewing the first animation, fewer students in both groups made statements claiming that the nitrate ions were the driving force for the reaction.

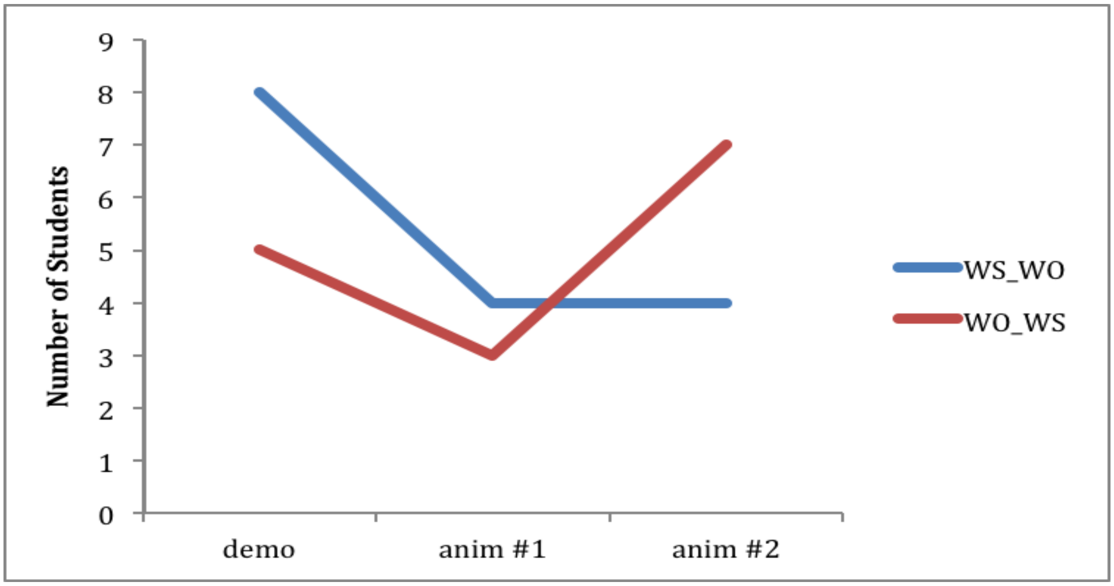


Figure 15. A plot of the number of students viewing the WS animation first and the WO animation second (WS_WO) and the number of students viewing the WO animation first and the WS animation second (WO_WS) claiming nitrate ions were the driving force for the reaction after viewing the demonstration (demo), the first animation (anim #1), and the second animation (anim #2)

However, there is an order effect after viewing the second animation: After initially viewing the animation with water molecules, none of the students in the WS_WO group changed their driving force answers to reference the nitrate ions after viewing the animation without water molecules; however, four students in the WO_WS group who initially viewed the animation without water molecules changed their driving force answers to include nitrate ions after viewing the animation with water molecules (z = 2.06, p = 0.02). This result is consistent with the result found by Rosenthal and Sanger (2013a) which showed that 90% of students viewing more complex animation followed by the more simplified animation in Figure 1 correctly identified the nitrate ions, while only 46% of students viewing the more simplified animation followed by more complex animation correctly identified the nitrate ions.

A quote from one of the WO_WS students who changed their answers after viewing the animation with water molecules appears below:

WO_WS Student: [After viewing the animation without water molecules] … random motion and collisions are driving this reaction, nitrates seem to be bystanders.

Same student: [After viewing the animation with water molecules] It looks like the nitrate facilitated the collision of copper and silver reacting.

Water Molecules Study – Results for Research Question 4

After viewing both animations, the students only mentioned one difference between the two animations: Whether the water molecules were shown or omitted from the animation. This difference was mentioned by every student who discussed how the two animations differed from each other. It is interesting to note that some students considered showing the water molecules to be an advantage while others thought that it is was a disadvantage. When asked which animation helped them understand the oxidation-reduction process better, more students (52) said they preferred the animation without water molecules, while fewer students (19) preferred the animation showing water molecules; only one student left this question blank ($\chi^2(1) = 14.222$, $p < 0.001$). The first two comments below came from students who considered the animation omitting water molecules to be more useful in understanding the oxidation-reduction process and the last comment came from a student who believed that the animation showing water molecules was more useful.

WS/WO Student: There was too much red and small with dots [in the WS animation] to be able to clearly see what was going on. Picking out [t]he Nitrogen was way more difficult with water represented in the animation.

WO/WS Student: With all of the water molecules, it became confusing to differentiate the ions from the water molecules. It became very busy.

WO/WS Student: It [WS animation] shows the H2O ions [sic] carrying the nitrate and silver ions towards the copper and bumping the copper out and then picking up the copper and leaving with it.

Results for Research Question 5 – Which Animations Should Be Shown in Class?

Students in both the visual complexity and the water molecules studies were asked which animation they thought should be shown in future classes when teaching about oxidation-reduction reactions. The results for this question appear in Table 5.

Table 5

The Number of Students From the Visual Complexity and the Water Molecules Studies Suggesting Which Animation(s) Should Be Shown in Class

Study	Neither	WO only	WS only	WO then WS	WS then WO
Visual complexity study (N = 55)	0	14	0	26	15
Water molecules study (N = 72)	4	18	12	17	21

For the visual complexity study , 14 of the 55 students (25%) felt that only the animation without water molecules should be shown, but none of these students felt that only the animation with water molecules should be shown or that neither animation should be shown. The other 75% felt that both animations should be shown. Of these students, 26 of the 41 (63%) said that the animation without water molecules should be shown first while the other 15 students (37%) felt that the animation with water molecules should be shown first. For the water molecules study, 18 of the 72 (25%) felt that only the animation without water molecules should be shown, 12 out of the 72 (17%) felt that only the animation with water molecules should be shown, and 4 of the 72 (6%) felt that neither animation should be shown. The other 53% felt that both animations should be shown: 17 of those 38 students (45%) felt that the animation without water molecules should be shown first while the other 21 (55%) felt that the animation with water molecules should be shown first. The distribution of students choosing each option was found to be significantly different for the students in the two studies ($\chi^2(4) = 17.42$, $p = 0.002$).

An analysis of the residual scores showed that fewer students in the visual complexity study and more students in the water molecules study felt that the instructor should show only the animation with water molecules present to students studying oxidation-reduction reactions. For students in the visual complexity study, the water-shown animation (the “more complex” animation by Tasker) and the water-omitted animation (the “more simplified” animation by Sanger) had several differences in addition to whether water molecules were shown or not (ion charges shown or absent, electrons were shown as a cloud or as particles, color change of solution shown or absent, static or moving camera angles, etc.). For the students in the water molecules study, however, the only difference between the two animations was whether the water molecules were shown or absent. Based on the results of the chi-square analysis, it appears that simply adding water molecules to the water-omitted animation in the water molecules study did not cause students to think that showing this animation alone would negatively affect future students' abilities to learn about oxidation-reduction reactions. However, the many differences between the two animations in the visual complexity study (including showing or omitting water molecules) did cause these students to believe that showing the water-omitted animation alone would negatively affect future students' abilities to learn about oxidation-reduction reactions.

Conclusions

In the first study described in this paper (the visual complexity study), students' explanations of the oxidation-reduction reaction occurring between aqueous silver nitrate and solid copper metal were compared after viewing the chemical demonstration and either a more simplified or more complex animation depicting the same chemical reaction at the particulate level. The statistical analyses showed that students viewing the more simplified animation were able to provide more correct explanations than students viewing the more complex animation related to the absence of ion pairs, a 1:1 ratio of silver and nitrate ions, a 2:1 reacting ratio of silver ions and copper atoms, the electron transfer process, the size changes of atoms and ions as the reaction occurs, the source of the blue color in solution, and the fact that water was not driving this reaction to occur. In addition, students were better at identifying the depictions of water and nitrate ions in the more simplified animation compared to the more complex animation. Students viewing the more simplified animation also provided more correct self-generated balanced equations than students viewing the more complex animation, suggesting that the more simplified animation may have been better at helping students' develop their representational competence (Sanger, 2009, Thomas, 2017) as they converted the particulate-level images they had seen into a symbolic-level balanced chemical equation. In general, it appears that instruction including the more simplified animation may have provided a more useful learning environment (enacted object of learning) that helped students develop a more robust mental model (lived object of learning) of the oxidation-reduction process (Bussey et al., 2013).

To probe the differences in the two learning environments created by these animations, the visual complexity study also analyzed comments from students regarding what they believed made the two different animations useful in understanding the oxidation-reduction reaction. These student comments suggested that one reason why they had difficulty interpreting the more complex animation is that it depicted extraneous material that distracted them from paying attention to the important information being shown. In particular, the changes in camera angle and the overabundance of water molecules in this animation were mentioned by students as major sources of distraction. Student comments also suggested that the more simplified animation provided more explicit (and more useful) depictions of information that was vital in understanding the oxidation-reduction reaction. These depictions included explicitly labelling the atom and ion charges, clearly showing the 1:1 ratio of silver and nitrate ions and the 2:1 reacting ratio of silver ions and copper atoms, explicitly showing the size changes of the atoms and ions as the reaction occurs, clearly showing the number of electrons transferred, and showing that the blue color of the solution became darker after each copper (II) ion was released. Some of these concepts were also depicted by the more complex animation (e.g., the 2:1 reacting ratio and the size changes), but because of the complexity of this animation, students were often unable to see or correctly interpret this information. Some of these concepts, however, were not depicted by the more complex animation (e.g., atom/ion charges, the number of electrons transferred, the source of the blue color); only one of these concepts appeared to be incorrectly depicted – the more complex animation showed more silver ions compared to nitrate ions in the reaction; presumably, this was done to reduce the complexity of the animation by showing fewer of the nitrate ions that are spectators in this reaction. Unfortunately, students noticed this simplification and it seemed to confuse or mislead some of those students. The more simplified animation showed each oxidation-reduction event occurring in the same spot and at the same time, compared to the more complex animation that showed these events as happening on different spots on the copper surface and at different times. As a result, for some concepts (such as the 2:1 reacting ratio of the silver ions and copper atoms and the electron transfer process) the more complex animation required students to work at a higher level in the Animation Processing Model (Lowe, 2014; Lowe & Boucheix, 2008) to understand the same concepts than the more simplified animation did, and that could explain why students were more successful in learning from the more simplified versus the more complex animation for those concepts.

Kelly *et al.* (2017) also asked students to provide particulate-level explanations (and drawings) of this oxidation-reduction reaction after viewing the same VisChem animation that was used in the visual complexity study (the “more complex” animation). This provides an opportunity to compare the results of two different research studies using the same animation; it should be noted that the Kelly’s study used the narrated version of this animation in their study while our study used a non-narrated version of the same animation. Kelly *et al.* (2017) noted that students often conflated the macroscopic properties of the chemical demonstration and the behavior of the particles in the oxidation-reduction process, and students often depicted these macroscopic properties in their particulate-level drawings of the chemical reaction. They also observed that students struggled with trying to depict the macroscopic color change of the solution in their particulate drawings. In general, they noted that, “…some students found it challenging to understand what the more complicated EEA [VisChem animation] depicted without a macroscopic connection” (Kelly et al., 2017, p. 591). Students in visual complexity study of this paper also seemed to have difficulty interpreting what was causing the color change in the VisChem animation, and it appears that showing the solution color change at the macroscopic level in the more simplified animation in the visual complexity study appeared to provide scaffolding that helped students interpret the particulate-level changes responsible for the macroscopic-level color change (Sanger, 2009; Thomas, 2017).

Students’ explanations of water’s possible behaviors in this reaction range from *present but not involved in the process* (“watching”) to *present and involved but not* *driving the reaction* (“assisting”) to *present and involved and driving the reaction* (“causing”). The goal of animations depicting this reaction should be to help students see that water molecules are present and involved but not driving the reaction. Kelly *et al.* (2017) found that after viewing both animations (the non-VisChem one showing water molecules as “watching” and the VisChem animation showing water molecules as “assisting”), students were more likely to draw pictures showing water molecules “watching”. Some students justified this idea by stating that since the water molecules do not appear in the symbolic balanced equation then they could not be involved in the particulate-level chemical reaction. The visual complexity study of this paper and other research studies (Tasker & Dalton, 2006; Rosenthal & Sanger, 2012, 2013a, 2013b), on the other hand, have noted that the way this VisChem animation depicts hydrated water molecules and their behaviors during this reaction actually caused students to believe that water molecules were the driving force for (“causing”) this reaction.

The results of the visual complexity study showed that students had much more success (and less difficulty) in interpreting the images presented in the more simplified animation compared to the more complex animation. However, these two animations depict the same copper metal-silver nitrate oxidation-reduction reaction in very different ways—including showing or omitting water molecules, the color changes of the solution as the reaction occurs, the charges of the ions in solution, correct silver to nitrate ratio, and changes in the camera angle; depicting the oxidation-reduction process as an event that occurs at the same place and time or showing it happening in different places and at different times, showing the electrons as particles or as a sphere of “fuzziness”, showing the correct silver to nitrate ion ratio, allowing the camera position to move, etc. Since there are so many differences in the way these animations depicted the oxidation-reduction process, it is impossible to determine from the visual complexity study alone which of these differences had a significant impact on students' abilities to interpret the images depicted in these animations and which of these differences were largely irrelevant. The goal of the water molecules study in this paper was to determine whether one of these factors (showing or omitting the water molecules in the animation) significantly affected students' abilities to understand the oxidation-reduction process.

The water molecules study examined student responses to questions about the copper metal-silver nitrate oxidation-reduction reaction after viewing a particulate-level animation of the reaction that differed only by showing or omitting water molecules. Analysis of the data indicated there were no differences between student responses for the two groups to questions about the presence of ion pairs in solution, the electron transfer process, recognizing the 1:1 ratio of silver ion and nitrate ion, recognizing the 2:1 reacting ratio of silver ions and copper atoms, and in writing a balanced equation for the reaction. The only significant difference between the responses from the two groups occurred when trying to identify the nitrate ions. Students viewing the animation showing water molecules had more difficulty correctly identifying the nitrate ions. The water molecules were depicted as a red sphere with two white spheres and the nitrate ions were depicted as a blue sphere with three red spheres. Both molecules were in motion during the animation and this "sea of red" would, undoubtedly, be a distraction when attempting to find and correctly identify the nitrate ions in the animation. Both studies presented in this paper found that having water molecules present confused students about the correct identity of the nitrate ions, and in both studies students misinterpreted the red-white water molecules as nitrate ions and attributed the motions and behaviors of the water molecules to the nitrate ions. Rosenthal and Sanger (2013a, 2013b) found significant order effects when using the two animations in the visual complexity study. In the water molecules study, however, no significant order effects were seen for any of the questions. Based on the results of Study 2, it seems reasonable to conclude that the significant order effects found by Rosenthal and Sanger (2013a, 2013b) were not the result of the presence or absence of water molecules depicted in the two animations.

In the water molecules study, we identified four categories for the students' explanations of the driving force for this reaction: Electronegativity arguments, stability (ΔG) arguments, viewing nitrate ions as the driving force~~s~~, and other miscellaneous arguments (including blank answers, "I don't know", and descriptions of *what* happened in the oxidation-reduction process and not *why* it happened). Although no significant order effects were found in the water molecules study for the correct answers, a significant order effect was found for one of the incorrect student responses as to why the reaction occurred (nitrate ions as the driving force). After viewing either animation, students were less likely to attribute nitrate ions as the driving force than they were before viewing either animation. Students who viewed the animation with water molecules shown first and then saw the animation with water molecules omitted second did not change their beliefs about nitrate's role in this reaction. However, students who viewed the animation with water molecules omitted first were more likely to suggest nitrates were driving the reaction after viewing the animation with water molecules shown. It is likely that this order effect may be due to the distraction of the sea of red and white water molecules moving in the background of the animation showing water molecules or the increased likelihood that students would confuse the water molecules and nitrate ions depicted in this animation.

Students in the water molecules study only identified one difference between the two animations—the presence or absence of water molecules. Unlike the visual complexity study, in which most student comments about the differences between the two animations seemed to favour a single animation, these comments seemed to have mixed results as to whether showing or omitting the water molecules would be more useful to future students. This result seems to suggest that showing or omitting water molecules in the two animations used in the visual complexity study is probably not responsible for students' opinions regarding which animation would be more useful to future students.

Students in both studies in this paper preferred the animation without water molecules over the animation showing water molecules. Students in the visual complexity study identified several issues that caused them to favor the more simplified animation over the more complex animation: it was less complex, it didn't show water molecules, it showed ion charges, it showed electrons as particles, and it showed the blue color of the solution. Students from both studies felt that the animation that did not show water molecules was less confusing and less distracting than the animations showing water molecules. While both groups had more students who would show only the animation without water molecules than those who would show only the animation with water molecules, when given a choice as to which animation(s) they would show in class, the majority of students in both studies suggested both animations be shown. The students felt that showing both animations provided a more complete picture of the copper metal-aqueous silver nitrate oxidation-reduction at the particulate level. This is consistent with the results from Kelly *et al.* (2017), which found that, even when one of the animations was purposefully animated to be inaccurate, students still saw merit in both animations and felt that future students could learn from both animations. Students in the visual complexity study were less likely to suggest showing only the animation without water molecules compared to students in the water molecules study. One reason for this difference could be that the animations in the visual complexity study differ by more than just whether water molecules were shown or omitted, and it could be those other differences that made the students in the visual complexity study less likely to recommend showing only the animation with water molecules.

Limitations and Implications

One major limitation to both of these studies is that the animations were used without the supporting narration. Mayer's multimedia learning theory (Mayer, 2009), as well as Paivio's dual coding theory (Paivio, 1986) and Baddeley's working memory model (Baddeley, 1986), asserts that students will learn better if provided information using both the visual and verbal channels (animations with narration) rather than using only the visual channel (non-narrated animation). Results from the visual complexity study suggest that students were better at interpreting the more simplified animation without the assistance of narration, but had difficulty interpreting the more complex animation without narration. It is possible that many of the differences in the students' explanations found in the visual complexity study may disappear or at least be diminished if the students had viewed the animations with narration, but further study would be needed to test this assertion. Kelly *et al.* (2017) found that students still experienced difficulty interpreting the VisChem animation used in the visual complexity study even with the narration included. These results also suggest that animators should carefully consider the narrations that accompany any animation to ensure that these narrations assist student learning by focusing on and explaining the relevant information (scaffolding), and minimizing or downplaying the effects of extraneous information depicted by the animation. Several researchers studying animations have observed that learning with animations can affect (Williamson *et al.*, 2013; Al-Balushi et al., 2017; Williamson *et al.*, 2013) or be affected by (Berney & Betrancourt, 2016; Höffler & Leutner, 2007; Lowe & Boucheix, 2008) the learner's spatial ability. Therefore, additional research studies should be performed to see whether the students' spatial abilities would affect (or be affected by) their interpretations of the animations used in this study.

Based on student-supplied quotes from the visual complexity study, Mayer's cognitive theory of multimedia (Mayer, 2009) can be used to explain why students who viewed the more simplified animation may have provided more correct and more complete explanations of the oxidation-reduction reaction depicted in the two animations than those who viewed the more complex animation. First, the more complex animation depicted extraneous material (the presence of water molecules and changing camera angles) that may have distracted students from identifying and attending to the important information being shown and overloading the students' visual working memory with extraneous information, consistent with Mayer's coherence principle (Mayer, 2009). Second, the more simplified animation depicted more explicit images (ion charges, electrons as particles, solution color changes) that may have helped students in selecting and organizing relevant images in their active cognitive processing of the presented material (Mayer, 2009). Other researchers (Chen, Schneps, & Sonnert, 2016; Kelly *et al.*, 2017) have found that simpler animations/simulations are more attractive to students than similar but more complicated animations/simulations, even when they impart more incorrect or incomplete knowledge to the learner compared to the more complex models. Chen *et al.* (2016) also postulated that a simpler model may pose obstacles for further student progress because it "anchors students' understanding, and they appear reluctant to change their conceptualization when exposed to a model that requires a higher cognitive load". This suggestion makes it even more imperative that designers of simpler animated sequences ensure that they depict scientifically accurate information and that simplifications requiring the use of incorrect or incomplete images or animated events should be avoided. The Animation Processing Model (Lowe, 2014; Lowe & Boucheix, 2008) can also be used to explain differences in students' abilities to interpret these two animations. Lowe and Boucheix (2008) noted that learners tend to be most affected by the negative aspects of an animation's dynamic motions if they are novices in the content area and if the animation's images are very complex. More complex images can affect both the learner's ability to correctly interpret the depicted images/motions and their ability to work with the large cognitive demands associated with the additional, more complex images. This is especially true for animations that are designed to be temporally and spatial consistent with the animated system (behaviorally realistic) because a learner can be distracted by irrelevant moving objects that catch the learner's attention but provide little relevant information to understand the concept of interest. In the case of the more complex animation, the constant movement of the water molecules may catch the student's attention but their motions provide little to no useful information to explain the electron transfer process between the silver ions and the copper atoms in the oxidation-reduction reaction depicted by the animation. Since the more simplified animation does not show the water molecules, the students are less likely to be distracted from the interactions of the silver ions and the copper atoms in the animation

In the water molecules study, the only difference in the visual images presented by the two animations was the presence or absence of the potentially distracting water molecules. The water molecules study showed that the addition of the water molecules in the animation had a very limited impact on students' understanding of the oxidation-reduction process occurring in the animations, and only seemed to affect their ability to correctly identify the red-white objects as water molecules and not nitrate ions. This result implies that whatever difficulty students in the visual complexity study had in interpreting the visual images of the more complex animation, the presence of water molecules in the animation did not have a huge distracting effect on these interpretations. Future research studies should investigate the other differences in the two animations in

Study 1 to determine which of these differences are responsible for the differences in the students' explanations of the oxidation-reduction process. Our research group is currently working on another study that is investigating the effect of showing or omitting the ion charges and on showing valence electrons as particles or as an outer shell on an atom.

Conflicts of Interest

There are no conflicts to declare.

REFERENCES

Al-Balushi, S. M., Al-Musawi, A. S., Ambusaidi, A. K., & Al-Hajri, F. H. (2017). The effectiveness of interacting with scientific animations in chemistry using mobile devices on grade 12 students' spatial ability and scientific reasoning skills. *Journal of Science Education and Technology*, *26,* 70-81. doi: 10.1007/s10956-016-9652-2

Akaygun, S. (2016). Is the oxygen atom static or dynamic? the effect of generating animations on students' mental models of atomic structure. *Chemistry Education Research and Practice*, *17,* 788-807. doi: 10.1039/c6rp00067c

Antonoglou, L. D., Charistos, N. D., & Sigalas, M. P. (2011). Design, development and implementation of a technology enhanced hybrid course on molecular symmetry: Students' outcomes and attitudes. *Chemistry Education Research and Practice, 12,* 454-468. doi: 10.1039/C0RP90013C

Ardac, D., & Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching*, *41,* 317-337. doi: 10.1002/tea.20005

Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.

Berney, S. & Betrancourt, M. (2016). Does animation enhance learning? A meta-analysis. *Computers & Education*, *101*, 150-167. doi: 10.1016/j.compedu.2016.06.005

Boo, H. K. (1998). Students' understandings of chemical bonds and the energetics of chemical reactions. *Journal of Research in Science Teaching*, *35,* 569-581. doi: 10.1002/(SICI)1098-2736(199805)35:5<569::AID-TEA6>3.0.CO;2-N

Brandriet, A. R., & Bretz, S. L. (2014). Measuring meta-ignorance through the lens of confidence: examining students' redox misconceptions about oxidation numbers, charge, and electron transfer. *Chemistry Education Research and Practice, 15*, 729-746, doi: 10.1039/c4rp00129j

Bussey, T. J., Orgill, M. K., & Crippen, K. J., (2013). Variation theory: A theory of learning and a useful theoretical framework for chemical education research. *Chemistry Education Research and Practice*, *14,* 9-22. doi: 10.1039/c2rp20145c

Butts, B., & Smith, R. (1987). HSC chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education*, *17*, 192-201.

Chen, C., Schneps, M. H., & Sonnert, G. (2016). Order matters: Sequencing scale-realistic versus simplified models to improve science learning. *Journal of Science Education and Technology*. *25,* 806-823. doi: 10.1007/s10956-016-9642-4

De Jong, O., Acampo, J., & Verdonk, A. (1995). Problems in teaching the topic of redox reactions: Actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching*, *32,* 1097-1110. doi: 10.1002/tea.3660321008

Garner, R., Gillingham, M. G., & White, C. S. (1989). Effects of "seductive details" on macroprocessing and microprocessing in adults and children. *Cognition and Instruction*, *6*, 41-57. doi: 10.1207/s1532690xci0601_2

Garnett, P. J., & Treagust, D. F. (1992a). Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching*, *29*, 121-149. doi: 10.1002/tea.3660290204

Garnett, P. J., & Treagust, D. F. (1992b). Conceptual difficulties experienced by senior high school students of electrochemistry: Electrochemical (galvanic) and electrolytic cells. *Journal of Research in Science Teaching*, *29,* 1079-1099. doi: 10.1002/tea.3660291006

Gilbert, J. K., & Treagust, D. F. (2009). Towards a coherent model for macro, submicro, and symbolic representations in chemical education. In J. K. Gilbert & D. F. Treagust (Eds.), *Models and modeling in science education: Multiple representations in chemical education* (pp. 333-350). Dordrecht: Springer-Verlag. doi: 10.1007/978-1-4020-8872-8

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: strategies for qualitative research*. New York: Aldine.

Gregorious, R. Ma., Santos, R., Dano, J. B., Guiterrez, J. J. (2010a). Can animations effectively substitute for traditional teaching methods? Part I: Preparation and testing materials. *Chemistry Education Research and* Practice, *11*, 253-261. doi: 10.1039/C0RP90006K

Gregorious, R. Ma., Santos, R., Dano, J. B., Guiterrez, J. J. (2010b). Can animations effectively substitute for traditional teaching methods? Part II: Potential differentiated learning. *Chemistry Education Research and* Practice, *11,* 262-266. doi: 10.1039/C0RP90007A

Harp, S. F., & Maslich, A. A. (2005). The consequences of including seductive details during lecture. *Teaching of* P*sychology*, *32*, 100-103. doi: 10.1207/s15328023top3202_4

Höffler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction.*, **17**, 722-738. doi: 10.1016/j.learninstruc.2007.09.013

Johnstone, A. H. (2006). Chemical education research in Glasgow in perspective. *Chemistry Education Research and* P*ractice*, *7*, 49-63. doi: 10.1039/B5RP90021B

Johnstone, A. H. (2010). You can't get there from here. *Journal of Chemical Education, 87,* 22-29. doi: 10.1021/ed800026d

Kelly, R. M. (2014). Using variation theory with metacognitive monitoring to develop insights into how students learn from molecular visualizations. *Journal of Chemical Education, 91,* 1152-1161. doi: 10.1021/ed500182g

Kelly, R. M., Akaygun, S., Hansen, S. J. R., & Villalta-Cerdas, A. (2017). The effect that comparing molecular animations of varying accuracy has on students' submicroscopic explanations. *Chemistry Education Research and* P*ractice, 18,* 582-600. doi: 10.1039/c6rp00240d

Kelly, R. M., & Jones, L. L. (2007). Exploring how different features of animations of sodium chloride dissolution affect students' explanations. *Journal of Science Education and Technology*, *85,* 303-309. doi: 10.1007/s10956-007-9065-3

Kelly, R. M., & Jones, L. L. (2008). Investigating students' ability to transfer ideas learned from molecular animations to the dissolution process. *Journal of Chemical Education, 85*, 303-309. doi: 10.1021/ed085p303

Lee, H., Plass, J. L., & Homer, B. D. (2006). Optimizing cognitive load for learning from computer-based science simulations. *Journal of Educational Psychology*, *98,* 902-913. doi: 0.1037/0022-0663.98.4.902

Liu, X., & Lesniak, K. (2006). Progression in children's understanding of the matter concept from elementary to high school. *Journal of Research in Science Teaching*, *43,* 320-347. doi: 10.1002/tea.20114

Loh, A. S. L., & Subramaniam, R. (2018). Mapping the knowledge structure exhibited by a cohort of students based on their understanding of how a galvanic cell produces energy. *Journal of Research in Science Teaching*, *55,* 777-809, doi: 10.1002/tea.21439

Lowe, R. K. (2004). Animations and learning: Value for money?, in R. Atkinson, C. McBeath, D. Jonas-Dwyer and R. Phillips (eds.), *Beyond the comfort zone: Proceedings of the 21st ASCILITE Conference*, Perth: ACSILITE, pp. 558-561.

Lowe R. K., (2014), Dynamic visualizations: A two-edged sword?, in W. Huang (ed.), *Handbook of human centric visualization*, New York: Springer, pp. 581-604.

Lowe R. K. and Boucheix J.- M., (2008), Learning from animated diagrams: How are mental models built?, in G. Stapleton, J. Howse, and J. Lee (eds.), *Diagrammatic representation and inference*, Berlin: Springer, pp. 266-281.

Lu, S., & Bi, H. (2016). Development of a measurement instrument to assess students' electrolyte conceptual understanding. *Chemistry Education Research and Practice*, *17*, 1030-1040. doi: 10.1039/C6RP00137H

Lu, S., Bi, H., & Liu, X. (2018). The effects of explanation-driven inquiry on students' conceptual understanding of redox. *International Journal of Science Education*, *40*, 1857-1873. doi: 10.1080/09500693.2018.1513670

Lu, S., Bi, H., & Liu, X. (2019). A phenomenographic study of 10th grade students' understanding of electrolytes. *Chemistry Education Research and Practice*, *20*, 204-212. doi: 10.1039/C8RP00125A

Mayer, R. E. (2009). *Multi-media learning*. Cambridge, UK: Cambridge University Press.

Moreno, R., & Mayer, R. E. (2000). A coherence effect in multimedia learning: The case for minimizing irrelevant sounds in the design of multimedia instructional messages. *Journal of Educational* P*sychology*, *92*, 117-125. doi: 10.1037/0022-0663.92.1.117

Nyachwaya, J. M. (2016). General chemistry students' conceptual understanding and language fluency: Acid-base neutralization and conductometry. *Chemistry Education Research and* P*ractice*, *17*, 509-522. doi: 10.1039/C6RP00015K

Nyachwaya, J. M., Mohamed, A. –R., Roehrig, G. H., Wood, N. B., Kern, A. L., & Schneider, J. L. (2011). The development of an open-ended drawing tool: an alternative diagnostic tool for assessing students' understanding of the particulate nature of matter. *Chemistry Education Research and* P*ractice*, *12*, 121-132. doi: 10.1039/C1RP90017J

Orgill, M. K. (2007). Phenomenography. In G. M. Bodner, & M. K. Orgill (Eds.), *Theoretical frameworks for research in chemistry/science education* (pp. 132-151). Upper Saddle River, NJ: Prentice Hall

Osman, K., & Lee, T. T. (2014). Impact of interactive multimedia module with pedagogical agents on students' understanding and motivation in the learning of electrochemistry. *International Journal of Science and Mathematics Education, 12*, 395-421. doi: 10.1007/s10763-013-9407-y

Paivio, A., (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.

Phelps, A. J. (1994). Qualitative methodologies in chemical education research: Challenging comfortable paradigms. *Journal of Chemistry Education*, *71*, 191-194. doi: 10.1021/ed071p191

Qualtrics [software]. (2015). Provo, UT, USA: Qualtrics. Retrieved from http://www.qualtrics.com

Rosenthal, D. P., & Sanger, M. J. (2012). Student misinterpretations and misconceptions based on their explanations of two computer animations of varying complexity depicting the same oxidation-reduction reaction. *Chemistry Education Research and Practice*, *13*, 471-483. doi: 10.1039/c2rp20048a

Rosenthal, D. P., & Sanger, M. J. (2013a). How does the order of viewing two computer animations of the same oxidation-reduction reaction affect students' particulate-level explanations? In J. P. Suits & M. J. Sanger, (Eds.), P*edagogic roles of animations and simulations in chemistry courses* (pp. 313-340). Washington, DC: American Chemical Society. doi: 10.1021/bk-2013-1142.ch013

Rosenthal, D. P., & Sanger, M. J. (2013b). How does viewing one computer animation affect students' interpretations of another animation depicting the same oxidation-reduction reaction? *Chemistry Education Research and Practice*, *14*, 286-296. doi: 10.1039/c3rp00006k

Russell, J. W., Kozma, R. B., Jones, T., Wykoff, J., Marx, N., & Davis, J. (1997). Use of simultaneous-synchronized macroscopic, microscopic, and symbolic representations to enhance the teaching and learning of chemical concepts. *Journal of Chemical Education*, *74*, 330-334. doi: 10.1021/ed074p330

Ryoo, K., Bedell, K., & Swearingen, A. (2018). Promoting linguistically diverse students' short-term and long-term understanding of chemical phenomena using visualizations. *Journal of Science Education and Technology, 27*, 508-522. doi: 10.1007/s10956-018-9739-z

Sanger, M. J. (2009). Computer animations of chemical processes at the molecular level. In N. J. Pienta, M. M. Cooper, & T. J. Greenbowe (Eds.), *Chemist's guide to effective teaching, Vol. II* (pp. 198-211). Upper Saddle River, NJ: Prentice Hall.

Sanger, M. J., Brecheisen, D. M., & Hynek, B. M. (2001). Can computer animations affect college biology students' conceptions about diffusion & osmosis? *The American Biology Teacher, 63,* 104-109. doi: 10.2307/4451051

Sanger, M. J., & Greenbowe, T. J. (1997a). Common student misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells. *Journal of Research in Science Teaching, 34,* 377-398. doi: 10.1002/(SICI)1098-2736(199704)34:4<377::AID-TEA7>3.0.CO;2-O

Sanger, M. J., & Greenbowe, T. J. (1997b). Students' misconceptions in electrochemistry: Current flow in electrolyte solutions and the salt bridge. *Journal of Chemical Education, 74,* 819-823. doi: 10.1021/ed074p819

Sanger, M. J., & Greenbowe, T. J. (2000). Addressing student misconceptions concerning electron flow in aqueous solutions with instruction including computer animations and conceptual change strategies. *International Journal of Science Education*, *22,* 521-537. doi: 10.1080/095006900289769

Sanger, M. J., & Phelps, A. J. (2007). What are students thinking when they pick their answer?: A content analysis of students' explanations of gas properties. *Journal of Chemical Education*, *84*, 870-874. doi: 10.1021/ed084p870

Sanger, M. J., Phelps, A. J., & Fienhold, J. (2000). Using a computer animation to improve students' conceptual understanding of a can-crushing demonstration. *Journal of Chemical Education, 77,* 1517-1520. doi: 10.1021/ed077p1517

Schmidt, H. –J., & Marohn, A., & Harrison, A. G. (2007). Factors that prevent learning in electrochemistry. *Journal of Research in Science Teaching*, *44*, 258-283. doi: 10.1002/tea.20118

Smith, K. C., & Nakhleh, M. B. (2011). University students' conceptions of bonding and melting and dissolving phenomena. *Chemistry Education Research and* P*ractice, 12*, 398-408. doi: 10.1039/C1RP90048J

Smith, K. J., & Metz, P. A. (1996). Evaluating student understanding of solution chemistry through microscopic representations. *Journal of Chemical Education, 73*, 233-235. doi: 10.1021/ed073p233

Suits J. P. and Sanger M. J., (2013), Dynamic visualizations in chemistry courses, in Suits J. P. and Sanger M. J. (ed.), Pedagogic Roles of Animations and Simulations, ACS Symposium Series, Washington DC: American Chemical Society, vol. 1142, pp. 1–13. doi**:** 10.1021/bk-2013-1142.ch001

Supasorn, S. (2015). Grade 12 students' conceptual understanding and mental models of galvanic cells before and after learning by using small-scale experiments in conjunction with a model kit. *Chemistry Education Research and Practice*, *16*, 393-407. doi: 10.1039/C4RP00247D

Sweller J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction.*, *4*, 295-312. Retrieved from http://coral.ufsm. br/tielletcab/Apostilas/cognitive_load_theory_sweller.pdf

Sweller, J., & Chandler, P. (1994), Why some material is difficult to learn. *Cognition and Instruction*, *12*, 185-233. Retrieved from https://www.researchgate.net/profile/Paul_Chandler3/publication/ 49249476_Why_Some_Material_Is_Difficult_to_Learn/links/ 0a85e5300f4b44c939000000.pdf

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry "triplet". *International Journal of Science Education*, *33*(2), 179-195. doi: 10.1080/09500690903386435

Talib, O., Matthews, R. & Secombe, M. (2005). Computer-animated instruction and students' conceptual change in electrochemistry: Preliminary qualitative analysis. *International Education Journal*, *5*, 29-42. Retrieved from https://files.eric.ed.gov/fulltext/EJ903885.pdf

Tasker, R. (1998). The VisChem project: Molecular level animations in chemistry—Potential and caution. *UniServe science news*, *9*, 12-16. Retrieved from http://science.uniserve.edu.au/newsletter/vol9/vol9.pdf

Tasker, R. (2005). Using multimedia to visualize the molecular world: Educational theory into practice. In N. J. Pienta, M. M. Cooper, & T. J. Greenbowe (Eds.), *Chemist's guide to effective teaching, Vol. I* (pp. 195-211). Upper Saddle River, NJ: Prentice Hall.

Tasker, R., & Dalton, R. (2006). Research into practice: Visualisation of the molecular world using animations. *Chemistry Education Research and Practice*, *7*, 141-159. doi: 10.1039/b5rp90020d

Thomas, G. P. (2017). 'Triangulation': An expression for stimulating metacognitive reflection regarding the use of 'triplet' representations for chemistry learning. *Chemistry Education Research and Practice, 18*, 533-548. doi: 10.1039/C6RP00227G

Tien, L. T., Teichert, M. A., & Rickey, D. (2007). Effectiveness of a MORE laboratory module in prompting students to revise their molecular-level ideas about solutions. *Journal of Chemical Education*, *84*, 175-181. doi: 10.1021/ed084p175

Tsaparlis, G. (2018). Teaching and learning electrochemistry. *Israel Journal of Chemistry*, *58*, 1-16. doi: 10.1002/ijch.201800071

Williamson, V. M. & 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. doi: 10.1002/tea.3660320508

Williamson, V. M., Lane, S. M., Gilbreath, T., Tasker, R., Ashkenazi, G., Williamson, K. C., & Macfarlane, R. D. (2012). The effect of viewing order of macroscopic and particulate visualizations on students' particulate explanations. *Journal of Chemical Education, 89,* 979-987. doi: 10.1021/ed100828x

Williamson, V. M., Watkins, J. T., & Williamson III, K. C. (2013). The effect of student-constructed animations versus storyboards on students' mental rotation ability, equilibrium content knowledge, and attitudes. In J. P. Suits & M. J. Sanger, (Eds.), P*edagogic roles of animations and simulations in chemistry courses* (pp. 293-311). Washington, DC: American Chemical Society. doi: 10.1021/bk-2013-1142.ch012

Yang, E., Andre, T., Greenbowe, T. J., & Tibell, L. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education*, *25,* 329-349. doi: 10.1080/09500690210126784

CHAPTER 3: DOES THE WAY CHARGES AND TRANSFERRED ELECTRONS ARE DEPICTED IN AN OXIDATION-REDUCTION ANIMATION AFFECT STUDENTS' EXPLANATIONS?

Martin H. Cole

Physical Sciences Department, Holyoke Community College, Holyoke, MA 01040

Dana K. Fuller

Department of Psychology, Middle Tennessee State University, Murfreesboro, TN 37132

Michael J. Sanger

Department of Chemistry, Middle Tennessee State University, Murfreesboro, TN 37132

Abstract

The study presented in this paper compares students' explanations of the oxidation-reduction reaction between silver nitrate and copper metal after viewing a chemical demonstration and one of four different particulate-level computer animations. The animations differed in the way the ionic charges were depicted (labeled or omitted) and the way the transferred electrons were depicted (as discrete e^- particles or as a fuzzy electron cloud/halo around the metal atoms). Students viewing animations explicitly labeling the ion charges were better at determining the number of electrons gained by each silver ion and lost by each copper atom and were able to write a more correct balanced chemical equation for the reaction than students viewing animations with the ion charges omitted. Compared to students who viewed animations depicting the transferred electrons as halos around the metal atoms, students viewing animations that depicted transferred electrons as discrete particles provided better explanations for the

number of electrons gained by the silver ions and lost by the copper atoms, and the relative sizes of the silver/copper atoms and their respective cations. Based on interview comments from students viewing animations with the charges shown and with charges omitted, it appears that several students did not know the proper charges of the silver, copper(II), and nitrate ions and that animations showing these charges provided students with relevant visual information that they could use to improve their pictorial models of the reaction depicted in these animations, which also led to improved student-generated balanced equations for this reaction. Similarly, student interview comments also demonstrated that when the animations depicted the transferred electrons as discrete particles, the animations provided students with more relevant visual images (the number of electrons being transferred to the silver ions from the copper atom in the reaction and the relative sizes of the metal atoms and their cations) that were not provided to students viewing animations with the transferred electrons depicted as the non-qualitative halos. Students shown these relevant visual images were more likely to construct accurate pictorial models of the oxidation-reduction reaction. The student interview comments also demonstrated that when the students were not explicitly provided relevant information (ion charges, number of electrons transferred, relative sizes of the metal atoms and ions) by the visual images in the animations, these students were forced to rely on their (often-inaccurate) preexisting domain-specific chemical knowledge to construct their pictorial models. The results of this study and a previous study by our research group suggest that, in animations depicting the oxidation-reduction reaction of silver nitrate and copper metal at the particulate level, showing or omitting water molecules in

the animations had little effect but showing or omitting the ion charges and depicting the transferred electrons as particles or halos in the animations had a significant impact on the students' explanations of the oxidation-reduction process.

Keywords

Audience: High School/Introductory Chemistry, First-Year Undergraduate/General

Domain: Chemical Education Research

Pedagogy: Discrepant Events, Multimedia-Based Learning

Topic: Aqueous Solution Chemistry; Electrochemistry; Oxidation/Reduction

Introduction

Chemistry's focus on abstract concepts, along with the interrelated nature of these abstract concepts, makes learning chemistry difficult for many students (Burrows & Mooring, 2015; Loh & Subramaniam, 2018). Some of this difficulty can be attributed to the triad nature of chemistry – the interconnection between the macroscopic, particulate, and symbolic conceptual levels of the subject and the need for students to not only work proficiently at all three levels, but to also see and make connections among these levels (Gilbert & Treagust, 2009; Johnstone, 2006, 2010; Sirhan, 2007; Talanquer, 2011; Tasker, 2005). Although several content areas/concepts in chemistry have been identified as being difficult for students to learn (e.g., Sirhan, 2007, and the references within this paper), the concepts associated with oxidation-reduction reactions and electrochemistry are often listed as some of the most difficult for students to learn (Davies, 1991; De Jong & Treagust, 2002; Griffiths, 1994; Tsaparlis, 2018).

Several student misconceptions in oxidation-reduction reactions and electrochemistry have been identified in the literature, including the notions that oxidation states can be assigned for molecules and polyatomic ions (Brandriet & Bretz, 2014; Garnett & Treagust, 1992a), the indirect reaction in a galvanic cell is different than the direct reaction (Sanger & Greenbowe, 1997a), the signs on the electrodes in an electrochemical cell represent electronic charges that direct the flow of electrons and ions (Garnett & Treagust, 1992a; Sanger & Greenbowe, 1997a; Schmidt, Marohn, & Harrison, 2007; Loh & Subramaniam, 2018), oxidation and reduction half-reactions can occur separately and independently from each other (Garnett & Treagust, 1992a; Sanger & Greenbowe, 1997a), electricity flow causes electrolyte compounds to decompose into ions (Ogude & Braddley, 1996; Schmidt, Marohn, & Harrison, 2007), free electrons can flow in aqueous solutions (Garnett & Treagust, 1992a; Sanger & Greenbowe, 1997a; Schmidt, Marohn, & Harrison, 2007; Loh & Subramaniam, 2018), positive and negative ions in an electrochemical cell carry electrons from one electrode to another (Garnett & Treagust, 1992a; Ogude & Braddley, 1996; Sanger & Greenbowe, 1997a; Schmidt, Marohn, & Harrison, 2007; Loh & Subramaniam, 2018), the flow of electrons in the electrolyte solution causes the oxidation and reduction process to occur at each electrode (Loh & Subramaniam, 2018), and water molecules will not react or be electrolyzed in electrolytic cells (Garnett & Treagust, 1992b; Sanger & Greenbowe, 1997a; Tsaparlis, 2018). Several researchers have also made suggestions as to why students have difficulty learning oxidation-reduction and electrochemistry concepts, such as: The use of vague or misleading language by students and teachers in the classroom (Garnett *et al.*, 1990; De

Jong, Acampo, & Verdonk., 1995; De Jong & Treagust, 2002; Loh & Subramaniam, 2018) and by textbook authors (Ogude & Braddley, 1996; Özkaya, 2002; Sanger & Greenbowe, 1999; Schmidt, Marohn, & Harrison, 2007), students misapplying concepts to new but inappropriate situations (Garnett, Garnett, & Treagust, 1990; Loh & Subramaniam, 2018), students' lack of appropriate prerequisite knowledge (Garnett & Treagust, 1992a; Özkaya, 2002; Tsaparlis, 2018), the use of the term/concept "electrical circuit" which causes students to think of electricity as the flow of electrons in an uninterrupted closed loop (Garnett et al., 1990; Loh & Subramaniam, 2018; Schmidt, Marohn, & Harrison, 2007), the description of the "positive" and "negative" signs or poles for the electrodes in an electrochemical cell (Ogude & Braddley, 1996; Sanger & Greenbowe, 1999; Schmidt, Marohn, & Harrison, 2007), and calculating the cell potential for an electrochemical cell using the "additive" method instead of the "difference" or European method (Sanger & Greenbowe, 1999; Tsaparlis, 2018). Loh and Subramaniam (2018) agreed with the Advanced Placement Chemistry Test examiner's reports from 2013 (quoted in that paper) that in order for students to truly understand the chemical processes occurring in galvanic and electrolytic cells, chemistry instructors need to teach students about these processes at the particulate level. Several chemical education research studies, summarized by Tsaparlis (2018) and Cole, Rosenthal, and Sanger (2019), have also indicated that computer animations at the particulate level can be particularly effective in helping students develop and improve their conceptual understanding of electrochemistry topics.

In general, computer animations of chemical processes at the particulate level have proven effective in aiding student understanding of various chemical concepts (Antonoglou, Charistos, & Sigalas, 2011; Ardac & Akaygun, 2004; Cole, Rosenthal, and Sanger, 2019; Gregorious, Santos, Dano, & Guiterrez, 2010a, 2010b; Kelly & Jones, 2007, 2008; Kelly, Phelps, & Sanger, 2004; Russell, et al., 1997; Ryoo, Bedell, & Swearingen, 2018; Sanger, 2009; Sanger, Brecheisen, & Hynek, 2001; Sanger, Phelps, & Fienhold, 2000; Tasker & Dalton, 2006; Williamson & Abraham, 1995; Williamson, et al., 2012) and can even improve students' spatial abilities (Al-Balushi, Al-Musawi, Ambusaidi, & Al-Hajri, 2017; Williamson, Watkins, & Williamson, 2013). Particulate-level animations have been shown to be effective in a wide variety of settings including whole classrooms (Herrington, Sweeder, & VandenPlas, 2017; Kelly, Phelps, & Sanger, 2004; Russell, et al., 1997; Sanger & Greenbowe, 2000; Smetana & Bell, 2014; Williamson & Abraham, 1995), small groups/pairs of students (Levy, 2013; Smetana & Bell, 2014; Yaseen, 2018), and individual students (Ardac & Akaygun, 2004; Chang, Quintana, & Krajcik, 2014; Gregorius, 2017; Kelly, Akaygun, Hansen, & Villalta-Cerdas, 2017; Sanger, Campbell, Felker, & Spencer, 2007). These animations have also been shown to be effective when they are student-generated (Akaygun, 2016; Chang et al., 2014; Williamson, et al., 2013; Yaseen, 2018) or researcher-generated (Gregorious, 2017; Kelly et al., 2017; Levy, 2013; Russell, et al., 1997; Sanger, et al., 2007; Sanger & Greenbowe, 2000; Tasker & Dalton, 2006; Williamson & Abraham, 1995; Yang et al. 2004).

Both Tasker (2005) and Kelly, Akaygun, Hansen, and Villalta-Cerdas (2017) have compared student's interpretations of computer animations depicting the particulate-level behavior of atoms, ions, and molecules in a scientifically accurate manner to animations with inaccurate or misleading visual images. Tasker (2005) included screen shots of animations created as part of the VisChem Project that accurately depicted the cations and anions from an aqueous ionic salt as being separated from each other and hydrated by water molecules in the solution and compared them to screen shots of another animation depicting neutral "molecules" of HCl and NaOH existing in water that were not hydrated by the surrounding water molecules. Tasker also provided examples of student-generated images of an aqueous barium chloride solution that matched the inaccuracies shown in the second animation (barium chloride existing in aqueous solutions as neutral "molecules"; isolated barium and chloride ions that were not hydrated by water molecules) and suggested that the use of inaccurate visual images during instruction could lead to student misconceptions (Tasker, 2005). Kelly et al. (2017) asked students to compare an accurate animation of the oxidation-reduction reaction of silver nitrate and copper metal in which the silver ions reacted with copper metal atoms to an animation created that inaccurately depicted silver nitrate "molecules" reacting with the copper metal, making silver metal atoms and copper(II) nitrate "molecules". Half of these students (9 of 17) indicated that they believed the animation without molecules was more scientifically accurate, but almost all students viewed both animations as being scientifically accurate and useful for students to understand the oxidation-reduction process. Even though more students chose the animation without molecules as being more accurate, more students changed their self-generated images and explanations to include information consistent with the visual images depicted in the inaccurate animation than the accurate animation. Part of this could be due to the fact that the students felt more comfortable in their ability to understand the visual images in the simpler but inaccurate animation compared to the more complex visual images in the animation deemed more accurate.

Kelly and Jones (2007) and Rosenthal and Sanger (2012) provided qualitative comparisons of students' explanations of a chemical event both before and after viewing two different animations of the event, both of which were animated to be scientifically accurate but using very different visual styles. Kelly and Jones (2007) asked students to explain the dissolving process of solid sodium chloride in water, while Rosenthal and Sanger (2012) asked students to explain the oxidation-reduction reaction occurring between aqueous silver nitrate and solid copper metal. Both studies had the same general format: students were asked to watch the macroscopic chemical demonstration and explain what was happening at the particulate level, then watch one of the animations and explain what was happening, and then watch the second animation and explain what was happening, followed by a debriefing in which students were asked to provide their thoughts and opinions about the animations and the instructional intervention involving those animations. Both studies found that the animations helped many students improve their particulate explanations of the chemical events, although some misconceptions remained after viewing the animations and other new misconceptions appeared that may be the result of simplified or incorrect visual images depicted in one of the animations.

Also, both sets of students overwhelmingly felt that the animations helped them understand the chemical event better and in greater detail (including relative atom and ion sizes), and their particulate explanations of the chemical event included specific comments related to the visual images they saw in these animations. Finally, both research groups indicated that students tend to interpret the visuals in animations rather literally and therefore suggested that simplifications depicting or implying incorrect concepts should be carefully avoided (Kelly & Jones, 2007; Rosenthal & Sanger, 2012).

More recently Cole, Rosenthal, and Sanger (2019) examined and quantitatively compared students' explanations of the oxidation-reduction process between aqueous silver nitrate and solid copper metal after viewing two sets of particulate-level animations depicting the same chemical reaction in different ways. In the visual complexity study described in this paper, the animations viewed by the students differed in the complexity of images used to depict the reaction: the more complex animation depicted three-dimensional images and showed camera angle changes and a large number of water molecules; the more simplified animation depicted two-dimensional images with no camera angle changes and no water molecules. In addition, the more simplified animation showed ion charges, electrons as particles, and macroscopic color changes of the blue background. Students who viewed the more simplified animation were better at identifying several key features in the oxidation-reduction reaction (a 1:1 ratio of silver and nitrate ions, 2:1 reacting ratio of silver ions and copper atoms, size changes of the copper atom and silver ions, and the source of the blue color in solution) and provided better explanations of the oxidation-reduction process (including the electron transfer process, the driving force of the reaction, and writing a symbolic balanced equation for the reaction) than the students who viewed the more complex animation. However, the way these two animations depicted the same reaction differed in so many aspects that it was difficult if not impossible to determine which of these differences led to the improvement of the students' explanations of the oxidation-reduction process. In the second study presented in the Cole, Rosenthal, and Sanger (2019) paper, the only difference between the two animations was whether water molecules were shown or omitted in the animation. The results of this study indicated that showing or omitting water molecules from the animation did not affect students' explanations of the oxidation-reduction process with the exception of identifying nitrate ions in the animation. Students who viewed the animation omitting water molecules were better at identifying nitrate ions in the animation than students who viewed the animation showing water molecules. As a result of this second study, the authors concluded that of the many differences in the way the visual information was presented in the more simplified and the more complex animations used in the visual complexity study, it was unlikely that showing or omitting water molecules in the animations had a significant impact on students' explanations of the oxidation-reduction process (Cole, et al., 2019).

The goal of this current study is to determine if students' explanations of the oxidation-reduction process will be affected when two other variables (the way in which the ion charges are visually depicted and the way in which the transferred electrons are visually depicted) within the animations are changed when all other visual images in the animation remain unchanged.

Research questions: (1) Does labeling or omitting the charges of all ions in the animation (silver, copper(II), nitrate ions) affect students' ability to explain the oxidation-reduction process? (2) Does depicting the electrons being transferred to silver ions from copper atoms as 'e–' particles or as a fuzzy cloud or halo affect students' ability to explain the oxidation-reduction processes? (3) Is there an interaction effect between the way the ion charges and the transferred electrons and ion charges depicted on students' explanations of the oxidation-reduction process?

Theoretical Framework

This study asked students to provide a particulate-level explanation and a symbolic-level balanced chemical equation after viewing a video of a macroscopic-level demonstration of the oxidation-reduction reaction between aqueous silver nitrate and solid copper metal and a single computer animation depicting the chemical reaction at the particulate level. As such, this study requires students to work with and interrelate three distinct, but related representational levels that chemists use to describe chemical reactions and other phenomena (Gilbert & Treagust, 2009; Johnstone, 2006, 2010; Talanquer, 2011; Tasker, 2005). These representational levels are the macroscopic (using visible and tangible information collected using the five senses), the particulate (using descriptions of atoms, ions, and molecules as well as their behaviors and interactions), and the symbolic (using the symbolic languages of numbers, chemical symbols, chemical formulas, balanced equations, etc.). While chemists can move effortlessly from one level to another and an make meaningful connections among them all, students often have difficulty making connections between these three levels and instruction using all three levels at once can lead to cognitive overload in students (Johnstone, 2010). Often, the explicit goal in many modern chemistry classrooms is to help students improve their ability to move between the levels of chemistry described above as a way to understand the complexity of many chemical processes (Thomas, 2017), which is referred to as *representational competence* (Sanger, 2009). This is often the goal for using particulate-level computer animations in chemistry instruction as well (Suits & Sanger, 2013).

Mayer's (2009) cognitive theory of multimedia learning indicates that multimedia presentations (such as computer animations) could be an effective educational tool in helping chemistry students make connections between the three levels and improve their conceptual understanding of chemistry. This theory was adapted from Paivio's dual-coding theory (Paivio, 1986), Baddeley's model of working memory (Baddeley, 1986) and cognitive load theory (Sweller, 1994, 1999). Mayer's cognitive theory of multimedia learning postulates that learners have two separate cognitive channels used for processing auditory (verbal) and visual (pictorial) information that each have limited processing capabilities, and that learners are actively engaged in the process of learning by attending to relevant information received, organizing that information into their existing mental schema, and integrating any new knowledge with their pre-existing knowledge.

For meaningful learning to occur in a multimedia environment, Mayer (2009) asserted that the learner must be actively engaged in five cognitive processes: Selecting relevant words, selecting relevant images, organizing selected words, organizing selected images, and integrating word-based and image-based representations. Since the animations used in this study do not have written or spoken words in them, the specific cognitive processes that are pertinent for students in this study are the selection and organization of relevant images in a multimedia presentation. Selection of relevant images by the learner of an animation occurs in the following manner: a picture impinges on the eyes producing a sensory image that does not require any effort on the part of the learner; this is followed by active processing at which time the learner must determine which images are important for making sense out of the animation; then the parts of the animation attended to by the learner will form a visual image base/mental representation in the working memory. During the cognitive process of organizing relevant images, the mental representations in the working memory are organized into an understandable structure – a mental scheme or “pictorial model” of what was presented (Mayer, 2009). Because of the learner’s limited processing capacity during the cognitive system, the learner can only select and pay attention to part of the visual images presented by the complex representations in the animation to produce his or her visual image base, and can only form a simple set of connections between the visuals in his or her image base in order to build a pictorial model. Since the learner can only focus on part of the incoming visual images to form a visual image base that leads to the learner’s pictorial model, he or she is forced to judge which visual images are the most relevant for making sense of the animation and use these images to construct a simple visual mental representation that makes sense to the learner. The design of the animation, including how the visual images are presented and organized, can affect the extraneous cognitive load that the learner experiences and can overload the learner and hinder or prevent learning (Clark, Nguyen, & Sweller, 2006; Mayer, 2009; Sweller, 1994; Sweller & Chandler, 1994).

Furthermore, the use of visual signaling or cueing can aide learners in selecting and organizing relevant visual information from a multimedia presentation. Visual cueing involves the addition of non-content visual information (e.g., arrows, distinctive colors, flashing images, etc.) to a multimedia presentation (Lin & Atkinson, 2011). As an example, Jeung, Chandler, and Sweller (1997) found that when the cognitive load associated with selecting relevant visual information from a geometry lesson was high, the addition of audio information to a visual lesson did not result in improved student performance but the addition of audio information along with flashing visual images did improve student performance. When the cognitive load associated with selecting relevant visual information from a geometry lesson was much lower, the addition of audio information improved student performance regardless of the use or omission of flashing visual images. The authors interpreted these results using cognitive load theory (Sweller, 1994, 1999) and hypothesized that when the cognitive load of the lesson was high, the addition of audio information to the visual images was not helpful because the students were already overloaded by the visual images and had little load available to process the new audio information; they argued that the use of flashing images lowered the necessary cognitive load to interpret the visual images and this allowed the students to process the new audio information. When the cognitive load of the lesson was low, the authors hypothesized that the students were not overloaded and were able to process the new audio information regardless of whether the flashing visual images were incorporated or missing. In general, research on visual cueing (Cao, 2005; Cook, Wiebe, & Carter, 2011; Jueng, Chandler, & Sweller, 1997; Patrick, Carter, & Wiebe, 2005; Schotz and Rasch, 2005) indicates that visual cueing methods are successful in directing the learner's attention to (selecting) relevant information to be used in developing (organizing) their mental models. Eye-tracking data collected by Ozcelik, Karakus, Kursun, and Cagiltay (2009) demonstrated that learners who found relevant information in a multimedia lesson faster tend to spend more time processing this information compared to their peers who spent more time finding this information, and this resulted in better performance on a transfer test (and therefore, an improved pictorial model) for the more time-efficient students.

Lowe and coworkers (Lowe, 2004; Lowe, 2014; Lowe & Boucheix, 2008) proposed a theory of learning from animated diagrams in response to their observation that theoretical developments with respect to research on learning from animations lagged behind the more ubiquitous empirical research studies in this field. They also noted that learners are most susceptible to the negative affects of animation design when they are novices in the field and when the visual images being presented are complex. Unlike previous theories of learning with animations (e.g., Mayer, 2009), which focused only on the cognitive aspects, Lowe and Boucheix (2008) developed a five-phase model (the animation processing model) that addresses both the perceptual and cognitive processes, as well as bottom-up (stimulus driven) and top-down (knowledge driven) contributions required to develop a dynamic pictorial model of depicted content.

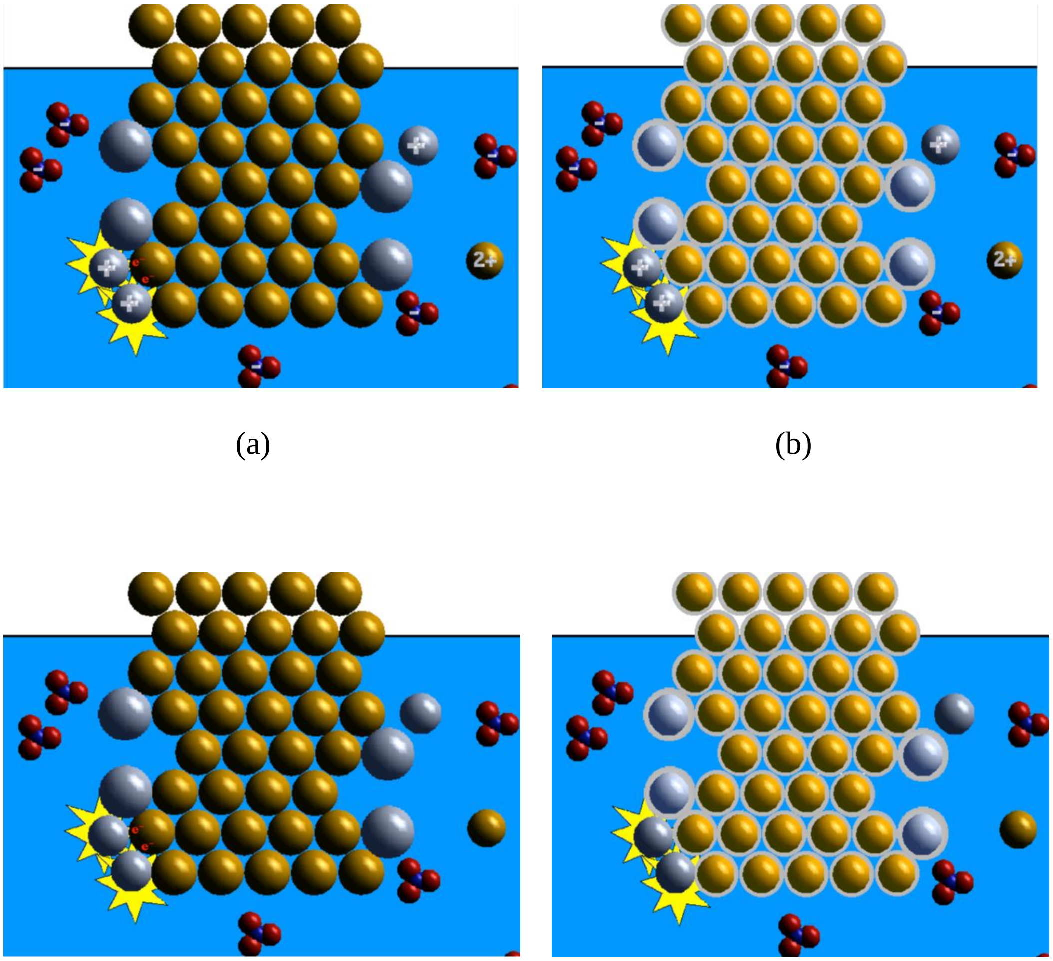
Although the animation processing model has five stages, novices in the subject are heavily dependent on the use the first three phases which demonstrate the stimulus-driven bottom-up contributions to information processing. Phase 1 focuses on the learner's initial bottom-up processes in which the learner starts by processing neighboring graphical images (often driven by the learner's opinions of the perceptual salience of these images); these processed graphical images and their behaviors/motions in the animation (called event units) serve as the raw material for Phase 2. In Phase 2 the learner starts to form regional structures known as "micro chunks" by linking the individual event units from Phase 1 into more coherent and complex structures based on similarities or perceived relationships between the event units. These micro chunks can be isolated from each other in space and time, are usually limited in scope, and are based on everyday world (i.e., not content-domain) knowledge. In Phase 3, the learner develops a comprehensive internal mental representation of the animation by bridging the often isolated micro chunks from Phase 2 over space and time. Unlike Phase 2, Phase 3 requires the learner to exhibit domain-specific knowledge. Without this domain-specific knowledge, the learner may wrongly characterize observed behaviors and relationships based on everyday general terms, or the learner may miss visually subtle but crucial information with subsequent negative impact on their dynamic pictorial model of the animation (Lowe & Boucheix, 2008).

Methods

Participants. College students at a comprehensive state university in the southeastern United States enrolled in first- (55.4 % female and 44.6 % male; average

age = 22.0) and second-semester (60.0 % female and 40.0 % male; average age = 23.6) general chemistry courses, taught by different instructors, were recruited to participate in this study. The students who participated in the online survey and the semi-structured interviews were randomly divided into four equally sized groups. Classroom instruction on electrochemistry and oxidation-reduction reactions was not accompanied by the use of animations for the survey students, but the interview students, who were taught by the last author, received classroom instruction that incorporated animations similar to the ones used in this study. The online survey students were asked to complete the survey as part of a research study during a laboratory session, after classroom instruction on oxidation-reduction reactions including balancing simple redox reactions. Instead of completing the laboratory experiment scheduled for that day, these students were taken to a computer laboratory by the first author to complete the online survey. These participants (N = 114) were compensated by receiving a laboratory score of 10/10 (with the permission from the laboratory coordinator). Students who did not volunteer for this study performed the scheduled experiment; the average scores for the laboratory reports in these labs were usually between 9.0-9.5/10 for these classes. Students participating in the interviews were asked to volunteer to be interviewed as part of the research study after receiving classroom instruction on the concepts of oxidation-reduction reactions and balancing more complex redox reactions in lecture. Their instructor gave each interview participant (N = 29) a small amount of bonus points (10 bonus points in a class with 750 points). The online surveys lasted from 20-60 minutes and the semi-structured interviews lasted from 60-120 minutes; the survey program Qualtrics (Qualtrics, Provo, UT) collected and recorded the written responses provided by both groups of students into a single report for subsequent data analysis. This research study was approved by the MTSU Institutional Review Board.

Computer animations. For this study, we used the animations depicted in Figure 16. The animation shown in Figure 16a was created by the third author as a 2-D particulate-level animation of the aqueous silver nitrate – solid copper metal – aqueous silver nitrate oxidation-reduction reaction and was used in previous studies by our research group (Cole, Rosenthal, & Sanger, 2019; Rosenthal & Sanger, 2012, 2013a, 2013b). This animation served as the basis for creating the other three animations, described below. This animation shows the charges on each of the ions and shows the transferred electrons as red “e^-“ symbols. In this animation, the solid copper metal is represented by golden spheres packed together in an organized pattern. The silver ions are depicted as gray spheres with a positive (+) charge in the middle of the sphere that float in the aqueous solution represented by a blue background. The nitrate ions appear as triangular shaped molecules, consisting of one blue nitrogen sphere surrounded by three red oxygen spheres with a negative (-) charge in the middle, also floating in the blue background. When two positively charged silver ion spheres strike the same neutral copper atom sphere, a yellow “flash” appears behind the two silver ion spheres. When these three objects come in contact, two red electrons (e^-) appear on the copper atom sphere and each of them is transferred from the copper atom sphere to one of the two silver ion spheres.



(a) (b)

(c) (d)

Figure 16. Screen shots from the four animations used in this study: (a) The animation with ion charges and with transferred electrons as particles, WC_EP, (b) the animation with ion charges but no transferred electron particles, WC_EH, (c) the animation with no ion charges but with transferred electrons as particles, NC_EP, and (d) the animation with no ion charges and no transferred electron particles, NC_EH.

When the electron transfer occurs, the copper atom sphere becomes smaller and positively charged (2+) and each silver sphere becomes larger and neutral (no charge). The two neutral silver atom spheres attach to the cluster of copper spheres while the positively charged copper ion sphere moves into the blue background. This process occurs four times throughout the animation; each time, the color of the background is changed to a darker blue shade to indicate the presence of more copper(II) ions in solution. The blue-red clusters move throughout the blue background and collide with several other objects, but do not change during the animation.

All four animations depict the same chemical species (silver ions, nitrate ions, copper atoms, silver atoms, and copper(II) ions) appearing at the same time and in the same place on screen, they all run for 24 seconds, and they were all non-narrated. The four animations differ in the way that they depict the charges of the ionic species in the animation and the way that they depict the transferred electrons. The animation in Figure 16a, which shows the charges on each of the ions and shows the transferred electrons as red "e^-" particles in the animation, was labeled WC_EP (with ion charges, with transferred electron as particles). In the animation shown in Figure 16b, the valence electrons on the silver and copper atoms are depicted as light gray outer halos – note that the copper and silver atoms with the halos appear lighter than in Figure 16a (an attempt to show that the halo completely surrounds these atoms), but the silver and copper ions without the halos are the same color as those in Figure 16a. When the electron transfer occurs, the copper atom loses its halo and is now a copper(II) ion with a '2+' label and the two silver ions each gain a halo indicating these ions had one electron transferred from the copper atom. Consequently, the silver ions lose their '+' label and become silver atoms. This animation was labeled WC_EH (with ion charges, no transferred electron particles). The animation in Figure 16c shows the transferred electrons as red "e^-" particles (as in Figure 16a) but the charges on the silver, copper(II), and nitrate ions have been omitted; this animation was labeled NC_EP (no ion charges, with transferred electrons as particles). Finally, the animation shown in Figure 16d uses halos to depict the valence electrons transferred to the silver ions from the copper atoms (as in Figure 16b) and omits the ion charges (as in Figure 16c); this animation was labeled NC_EH (no ion charges, no transferred electrons as particles).

Survey platform. For this study the Qualtrics survey platform (Qualtrics, Provo, UT) was used to generate the online survey. This platform allowed us to embed a video of the chemical demonstration and one of the four animations from Figure 16 within the survey and ask multiple-choice and open-response questions related to the demonstration and the animation in the survey. The survey questions (Figure 17) were adapted from the original research questions used in a previous study (Cole, Rosenthal, & Sanger, 2019) to more explicitly address important and relevant concepts identified from that study. Students used computers that were provided by the researchers to access the Qualtrics surveys (video demonstration, computer animation, and research questions) via a web address provided by Qualtrics.

Interview and survey protocol. The interviewed students completed the Qualtrics survey in the presence of the first and third researchers, using desktop computers in the third author’s office to complete the survey. As these students worked through the survey, the researchers encouraged the students to clarify and elaborate on their thoughts regarding the silver nitrate – copper metal oxidation-reduction reaction. Interviews were digitally recorded and transcribed by the first author. The remainder of the students involved in this study completed the same survey individually in a computer laboratory filled with other student participants and were not explicitly asked by the researchers to clarify or elaborate on their thoughts on the same oxidation-reduction reaction.

Each survey started with students watching a videotaped chemical demonstration of the aqueous silver nitrate – solid copper metal oxidation-reduction reaction. The students were then asked to answer the questions in Part 1 of the research protocol appearing in Figure 17.

Part 1: Questions asked after students had viewed the video demonstration of the aqueous silver nitrate and solid copper metal reaction.

1. How do you know a chemical reaction is occurring?
2. What substances are present at the beginning of the reaction?
3. Describe these substances at the beginning of the reaction.
4. What are the products of the reaction?
5. What is the function of each of the substances in the reaction?
6. Where does the reaction occur?
7. Why does the reaction occur?
8. Write a balanced equation for the reaction you saw in the video above.

Part 2: Questions asked after students had viewed one of the computer animations depicting the aqueous silver nitrate and solid copper metal reaction.

*1. In the animation, the silver ions: (a) lose electrons (b) gain electrons (c) have no change in electrons
2. How many electrons does each silver ion lose or gain?
*3. In the animation, the copper atoms: (a) lose electrons (b) gain electrons (c) have no change in electrons
4. How many electrons does each copper atom lose or gain?
*5. Which object is bigger, a copper atom or a copper ion? (a) copper atom (b) copper ion (c) they are the same size
*6. Which object is bigger, a silver atom or a silver ion? (a) silver atom (b) silver ion (c) they are the same size
7. Why does this reaction happen?
8. In the solution, there are ___ silver ion(s) for every ___ nitrate ion(s) present.
9. In the reaction, there are ___ silver ion(s) for every ___ copper atom(s) reacting.
10. Write a balanced equation for the reaction you saw in the animation above.

Figure 17. The interview protocol used during the semi-structured interviews and surveys in this study. The multiple-choice questions are marked with an asterisk; all other questions were open response.

Following the video demonstration, the students were asked to answer the questions in Part 2 of the research protocol after viewing one of the four different animations. The students were permitted to view the video and animation as many times as they wanted during the survey, but the surveys were designed so that once the students completed the chemical demonstration portion of the survey, they could not return to it after viewing the computer animation. One group of students (7 interview and 29 survey students) watched the animation showing ion charges and depicting the transferred electron as particles (WC_EP), the second group of students (7 interview and 28 survey students) viewed the animation showing ion charges and depicting the transferred valence electrons as halos on the silver and copper atoms (WC_EH), the third group of students (8 interview and 29 survey students) watched the animation omitting ion charges but showing the transferred electrons as particles (NC_EP), and the fourth group of students (7 interview and 28 survey students) watched the animation omitting ion charges and depicting the transferred valence electrons as halos on the silver and copper atoms (NC_EH).

Data analysis. The goal of this study was to compare students' answers to the questions in Part 2 of the research protocol (Figure 17) after they had viewed one of the four animations. The Qualtrics survey data were analyzed and scored by the first author. For questions 1-9 in Part 2 of the research protocol, students were given a score of "1" if they provided the scientifically accepted answer; otherwise, they were given a score of "0". Questions 7 and 10 were more complex and required the first and third researchers to reach a consensus on these answers. Students' answers to question 7 (the driving force of the reaction) were scored based on the four categories identified for the driving force in the second study described in a previous publication from our research group (Cole, Rosenthal, & Sanger, 2019) — only answers that focused on electronegativity or standard reduction potentials were given a score of "1"; all other answers were given a score of "0". For question 10 (balanced equation), we used the same 20-point scale reported in previous research studies from our group (Cole, Rosenthal, & Sanger, 2019; Rosenthal & Sanger, 2013a, 2013b). Several of these questions (1 and 3, 2 and 4, 5 and 6) measured similar concepts; in these cases, each student's scores for these pairs of questions were added together before performing a single statistical analysis. Analysis of these student scores was performed using a Two-Way Analysis of Variance (ANOVA) with the depiction of charges and the depiction of transferred electrons as the two independent variables. One advantage of performing a Two-Way ANOVA is that this analysis allowed the researchers to determine if there were any interaction effects between the students' interpretations of way the charges and the way the transferred electrons were depicted in each animation.

Results and Discussion

After viewing the chemical demonstration and one of the four animations, students' responses to questions about the following concepts were scored and analyzed: Determining whether silver ions and copper atoms gained or lost electrons, determining the number of electrons gained or lost by the silver ions and copper atoms, comparing atom and ion sizes for the same metal, explaining the driving force of the reaction, recognizing a 1:1 ratio between silver ions and nitrate ions in solution, recognizing a 2:1

reacting ratio between the silver ions and copper atoms, and writing a balanced equation for the reaction. Table 6 provides a summary of the statistical analyses of these comparisons. There were several significant main effects identified based on how the charges or the transferred electrons were depicted; however, no statistically significant interaction effects were identified between these two variables in the course of this study.

Table 6

Results for the Statistical Comparisons of Students' Responses after Viewing the Four Animations

	Main Effects				Interaction of Ion Charges x Transferred Electrons	
	Ion Charges		Transferred Electrons			
Concept	*F* (1,142)	*p*	*F* (1,142)	*p*	*F* (1,142)	*P*
Identifying species oxidized and reduced	0.123	0.727	2.929	0.089	0.054	0.816
Determining the number of electrons gained or lost	6.113	0.015[a]	5.188	0.024[a]	0.176	0.676
Comparing atom and ion sizes	0.224	0.637	5.019	0.027[a]	0.007	0.932
"Atoms and ions are the same size" (MISC)	0.981	0.324	6.157	0.014[a]	0.000	0.997
Identifying the reaction's driving force	1.419	0.236	0.067	0.796	0.081	0.776
Recognizing the 1:1 silver/nitrate ratio	0.231	0.631	0.240	0.625	0.231	0.631
Recognizing the 2:1 silver/copper ratio	0.001	0.981	0.094	0.759	0.406	0.525
Writing a balanced equation for the reaction	5.149	0.025[a]	0.035	0.851	2.512	0.115

[a] $p < 0.05$ corresponds to a significant difference between answers to the questions about the animations.

The least squares means and standard errors for all main effect comparisons appear in Table 7.

Table 7

Least Squares Means (Standard Errors) for the Main-Effect Comparisons of Students' Responses after Viewing the Four Animations Shown in Table 6

	Ion Charge Main Effect		*Transferred Electrons Main Effect*	
	Charges Omitted	Charges Shown	Electron Halos	Electron Particles
Identifying species oxidized and reduced	1.351^{b} (0.098)	1.303^{b} (0.099)	1.208^{b} (0.099)	1.446^{b} (0.098)
Determining the number of electrons gained or lost	0.824^{b} (0.092)^{a}	1.148^{b} (0.093)^{a}	0.837^{b} (0.093)^{a}	1.135^{b} (0.092)^{a}
Comparing atom and ion sizes	1.027^{b} (0.098)	1.093^{b} (0.099)	0.904^{b} (0.079)^{a}	1.216^{b} (0.098)^{a}
"Atoms and ions are the same size" (MISC)	1.757^{b} (0.076)	1.649^{b} (0.077)	1.568^{b} (0.077)^{a}	1.838^{b} (0.076)^{a}
Identifying the reaction's driving force	0.392^{c} (0.105)	0.569^{c} (0.106)	0.461^{c} (0.106)	0.500^{c} (0.105)
Recognizing the 1:1 silver/nitrate ratio	0.446^{c} (0.059)	0.486^{c} (0.059)	0.446^{c} (0.059)	0.486^{c} (0.059)
Recognizing the 2:1 silver/ copper ratio	0.608^{c} (0.057)	0.610^{c} (0.058)	0.597^{c} (0.058)	0.622^{c} (0.057)

Table 7 continued

	Ion Charge Main Effect		*Transferred Electrons Main Effect*	
	Charges Omitted	Charges Shown	Electron Halos	Electron Particles
Writing a balanced equation for the reaction	10.649[d] (0.788)[a]	13.195[d] (0.799)[a]	11.816[d] (0.799)	12.027[d] (0.788)

[a] These main effects were found to be significant different ($p < 0.05$).
[b] Maximum score 2
[c] Maximum score 1
[d] Maximum score 20

Identifying which chemical species were oxidized/reduced. In the previous research studies from our research group based on these and similar oxidation-reduction animations involving silver nitrate and copper metal (Cole, Rosenthal, & Sanger, 2019; Rosenthal & Sanger, 2013a, 2013b), the students' responses to first four questions in Part 2 of the research protocol (Figure 17) were combined into one four-point score measuring students' understanding of the oxidation-reduction process. In this study, we divided the oxidation-reduction process into two distinct concepts: Determining which chemical species gained or lost electrons (questions 1 and 3) and determining the number of electrons gained or lost by each chemical species (questions 2 and 4). This was done because we had anticipated that the animations could have different effects on students' understanding of these two concepts.

The statistical results in Table 6 show that there were no main effects for how the charges or transferred electrons were depicted in the four animations (both $p > 0.05$)

when comparing students’ answers about whether silver ions or copper atoms gained or lost electrons during the reaction (questions 1 and 3), in other words, the students’ explanations for which chemicals gained or lost electrons were independent of the visual images used by the animations. Whether the animation depicted transferred electrons as particles or as the appearance or disappearance of a halo, each method provided visual cues to students that the silver ions were gaining electrons (by gaining red “e^-” symbols and size increase or the appearance of the electron halo) and copper atoms were losing electrons (via the loss of the red “e^-” symbols and a size decrease or the disappearance of the electron halo). Therefore, it is not surprising that how the transferred electrons were depicted did not have a significant impact on students’ answers to these questions. Showing or omitting the ions charges did not appear to provide any additional relevant or distracting information that affected these students’ answers regarding which chemical gained or lost electrons either. In general, it appears that students were able to organize the visual images used by the four animations into comparable pictorial models of the direction of electron flow in this reaction (Mayer, 2009).

How many electrons were lost/gained. Students’ answers to the questions about how many electrons were gained or lost by the silver ions and copper atoms during the reaction (questions 2 and 4), on the other hand, showed a significant effect based on how the animations depicted charges ($F(1, 142) = 6.113$, $p = 0.015$) and how they depicted the transferred electrons ($F(1, 142) = 5.188$, $p = 0.024$). Students whose animations depicted ion charges were significantly better at determining the number of electrons gained or lost by silver ions and copper atoms during the reaction than those students whose animations omitted ion charges (1.135/2 versus 0.837/2, respectively) and students whose animations depicted transferred electrons as particles performed better than students whose animations depicted transferred electrons by the appearance or disappearance of a halo (1.148/2 versus 0.824/2, respectively).

Students who viewed the animations depicting ion charges were better at determining the number of electrons gained or lost by the silver ions and copper atoms than students viewing animations that omitted the ion charges. The student comments below show how this student used the ion/atom charges of the silver and copper species to determine the number of electrons gained or lost by the two reactants, and that these charges provided the relevant information the student needed to determine the direction and number of electrons transferred.

Online Survey (Part 2): 1. How many electrons does each silver ion lose or gain? Enter a number below:

WC_EH Student: One because it's going from plus one to neutral.

Interviewers: and you can see that from the …?

WC_EH Student: From the animation. Copper … It loses electrons. And it loses two electrons

Interviewers: So can you see it losing electrons in the animation?

WC_EH Student: Yes, well … I mean … We see the charge changing. Yes.

Interviewers: Ok, so you don't actually see the electrons …

WC_EH Student: Coming off, no.

Interviewers: But you can determine it because…

WC_EH Student: The change in the charge.

Interviewers: Ok. So charges are helping you.

WC_EH Student: Uh huh.

Interviewers: Ok good to know.

For the animations omitting the ion charges, the following student's comments show that the first step the student took in trying to determine the number of electrons silver gained was to look at the charges of the silver and copper ions, but the student was unsure of the charges of the silver and copper ions.

NC_EH Student: The silver ions gain electrons.

Interviewers: Ok.

NC_EH Student: From the copper.

Interviewers: Ok. Are you sure?

NC_EH Student: No.

Interviewers: That's ok. The next… The question underneath it is, is can we quantify? Can we tell how many electrons it's [silver ion] gained or lost?

NC_EH Student: From the video?

Interviewers: Yeah.

NC_EH Student: Um. Doesn't the charge have to [do] with it? Like …

Interviewers: Mm-hmm.

NC_EH Student: Aren't they both like 2+? Isn't A… isn't silver and copper 2+?

Interviewers: I'm not telling.

NC_EH Student: Ah, ugh.

Interviewers: But that's ok. So you think that silver and copper are both 2+, right?

NC_EH Student: Yes.

Interviewers: Ok let's go with that and see if that helps us.

NC_EH Student: So it would be two [the number of electrons silver gained].

Interviewers: Ok.

NC_EH Student: And then …

Interviewers: What happens to the coppers in all of that?

NC_EH Student: The opposite, they lose.

Interviewers: Ok.

(Part 2) How many electrons does each copper atom lose or gain? Enter a number below:

NC_EH Student: Two. I think.

Based on these student comments, it appears that the animations showing ion charges provided additional, relevant visual information (ion charges) needed by students to successfully determine the number of electrons gained or lost by the chemical species in the reaction, which allowed the learners to focus on and use the important information presented to develop a better pictorial model of the electron transfer process that might not be possible without this visual information (Mayer, 2009). For many students viewing the animations omitting the ion charges, they were missing this relevant information and instead had to rely on pre-existing (and in this case, faulty) domain-specific knowledge in order to interpret the animations without the ion charges depicted (Lowe, 2014; Lowe & Boucheix, 2008).

Students who viewed animations depicting transferred electrons as particles were also better able to determine the number of electrons gained or lost by the silver ions and copper atoms than those who viewed animations depicting transferred electrons as the appearance or disappearance of a halo. Students viewing the electron particles were able to actually see the number of electrons gained or lost by the silver ions and copper atoms in the reaction because of the red “e^{-}“ symbols moving from the copper atom to the silver ions. As the following quote illustrates, the movement of the red “e^{-}“ symbols proved to be relevant information for this student in determining the number of electrons gained or lost by the two reactants.

NC_EP Student: It looks like the copper is losing electrons. Ok.

Interviewers: So can you see that in the animation?

NC_EP Student: I think so, [be]cause it looked like it came out of the little copper.

Interviewers: So what came out of them?

NC_EP Student: The electrons.

Interviewers: Ok. So how are the electrons represented?

NC_EP Student: The little ‘e’ with the negative.

Interviewers: Ok. The little red ‘e-minuses’?

NC_EP Student: Uh huh. So the silver gained electrons then. [Be]Cause the copper … They’re losing two. Yeah, it looks the copper is losing two, and the silver. Well there are two silvers, so, and each one is gaining one electron.

The comments from a student who viewed an animation depicting the transferred electrons as halos showed that the student had a bit of difficulty determining that the silver ions gained electrons and the copper atom lost them, but after a bit of struggling the student committed to this idea. However, the student didn’t know how to determine how many electrons were transferred during this reaction. At this point, this student hadn’t been given the charges of the metal ions or the number of electrons transferred (as the little red “e^-” symbols), and without this relevant information, the student was stuck. Interestingly enough, the student did notice the 2:1 reacting ratio of the silver ions and copper atom and did see this as potentially relevant information, but the student didn’t know what to do with that information.

NC_EH Student: I mean they [silver ions] have a reaction when they … when they reach the copper. When it does the little thing … Yes the little outside thing [halo] …

Interviewers: Ok.

NC_EH Student: So it’s doing something. I’m just not too sure what it’s doing. Yeah, I see like it has an animation whenever it hits … It’s doing something. Ah, I’d say the copper gains electrons, right? [Be]Cause … Not copper. The copper is losing. The silver is gaining?

Interviewers: And how do you see that in the animation? Is it … is it showing you that?

NC_EH Student: Because it's … it does a little reaction [yellow flash] when it [silver ion] touches the copper … I think there's definitely a change because why would it have a little reaction when it hits. I think something changes. Well if the copper is losing something then I would think the silver was gaining something. I'm not completely …

Interviewers: And do you think that the loss and gain are electrons?

NC_EH Student: Possibly.

Interviewers: Ok.

NC_EH Student: So, I just wouldn't know how many. I … So silver is gaining, so copper would be losing. Losing yeah. And … how many? I mean one of those guys is floating off for every two silver, but I don't know what that means.

Interviewers: Ok. So you definitely noticed the two-to-one ratio right?

NC_EH Student: Mm-hmm. So maybe …

Interviewers: So do you think the two-to-one ratio is important?

NC_EH Student: Yes. I … I'm assuming it means that it has … it needs, ah, two silvers to make up for one copper, but …

Interviewers: Ok, but you're still a little unclear about what those answers are going to be, right?

NC_EH Student: Right.

Although the animations depicting the transferred electrons as particles explicitly shows two red “e^-” particles transferred to the silver ions from the copper atom, the animations depicting the transferred electrons as the appearance or disappearance of a halo do not quantify the number of electrons transferred in this reaction. As with the animations that did not depict the ion charges, the animations that do not depict the number of transferred electrons appear to be leaving out important visual information that students could use to figure out the number of electrons transferred to the silver ions from the copper atom. The visual images showing the number of red “e^-” particles being transferred allowed the learners to use this important information to develop a better visual pictorial model of the electron transfer process that might not be possible from the limited visual information provided by the halos (Mayer, 2009). Based on this result, it appears that it is not whether the transferred electrons were depicted as particles or halos that affected students’ explanations of the oxidation-reduction process, it was the fact that depicting the transferred electrons as particles provided quantitative information that was not provided by the use of halos. As a result, students viewing the animations with halos were provided with less useful visual information and, missing this relevant information, these students were forced to rely on (often inaccurate) pre-existing domain-specific content knowledge to interpret the visual images within these animations (Lowe, 2014; Lowe & Boucheix, 2008).

The positive effect of providing relevant visual information (ion charges and the number of transferred electrons) on students’ explanations of the number of electrons gained or lost by the silver ions and copper atoms in this study may also have been enhanced by the use of visual cues in all four animations. In this study, visual cueing took the form of yellow-colored “flashes” (appearing in the bottom left of each of the four animation screenshots in Figure 1) highlighting the site on the copper metal surface where the reaction between the stationary copper atom and the incoming silver ions occurred in each animation.

Interviewer: So the next one [copper metal-silver ion reaction] is going to happen right here [pointing to screen] so hit play and just watch.

WC_EP Student: It does a little ‘pow’ thing. Oh, you see it. You see it. You see it, dude!

So, if the use of the yellow flashes was the same in all four animations, then how is it possible that this consistent use of visual cueing had differential effects on the students’ abilities to determine how many electrons were transferred to the silver ion from the copper atom? It is likely that in all four animations, the yellow flashes on the copper surface did help direct students’ attention to the images of the incoming silver ions and the stationary copper atom on the copper surface. When these animations depicted relevant information in this highlighted area (e.g., the changes in electronic charges on the silver and copper species or the number of transferred electrons to the silver ions from the copper), then the students were more likely to pay attention to this relevant information and incorporate this information into their pictorial model, yielding more correct responses. However, when these animations did not depict relevant information in this highlighted area (by omitting the ion changes or by showing the electron transfer through the appearance or disappearance of non-quantitative halos), even students who were paying more attention to this particular site in the animation did not receive additional relevant information, did not adapt their pictorial model to incorporate this information, and therefore did not provide more correct responses.

Comparing atom and ion sizes. Comparison of the students' responses for determining the relative sizes of atoms and ions indicated no significant difference among those students who viewed animations depicting ion charges and those who viewed animations not depicting ion charges ($F(1, 142) = 0.224$, $p = 0.637$). However, students who viewed animations depicting transferred electrons as particles were better at determining relative atom and ion sizes (1.216/2) than those students who viewed animations depicting the electron transfer through the appearance and disappearance of halos (0.904/2), $F(1, 142) = 5.019$, $p = 0.027$. The animations depicting transferred electrons as red “e^-“ symbols (Figures 16a and 16c) represented the silver and copper atoms as solid spheres that are the same color as the silver and copper ions, only larger. The animations depicting the outer electrons as halos (Figures 16b and 16d), on the other hand, kept the size of the nucleus and core electrons the same, and added or removed the halo to make atoms or ions (respectively). The difficulty some students have is that they are not sure whether they should include the halo in the size of the atoms or not (Rosenthal & Sanger, 2012).

Students viewing animations without the halos did not seem to have difficulty in correctly comparing the sizes of the metal atoms and ions depicted in the animations.

Interviewer: … So you go back to the video and see what's going to be bigger?

WC_EP Student: Silver, Ag ions are smaller and their atoms are bigger.

Interviewer: Well, what did you see for copper …?

WC_EP Student: Yeah, they're bigger then they go smaller. … So they turn into ions and then get smaller. So it's the same thing. So, the copper atom is bigger than the copper ions. And then the silver atom is bigger.

Interviewer: And that was evident in the video?

WC_EP Student: Yes.

However, some students viewing animations with the electron halos incorrectly assumed that the halos did not affect the atom size, and therefore they expected the sizes of the metal atom and its ion to be the same. Interestingly, this student (and others in the interview pool) suggested that the reason the metal atom and ions are about same size is that electrons themselves are very small in mass or volume, and therefore shouldn't affect the atom's or ion's sizes appreciably.

WC_EH Student: Which is bigger [copper ion or copper atom]…? They look about the same. Yeah, there is not very much space in an electron though, so… Ha. They're about the same.

The statistical analysis for the "Comparing atom and ion sizes" in Tables 6 and 7 compared the number of correct responses (metal atoms are bigger than cations of the same element) from students viewing the four animations; however, we were also interested in comparing the number of students providing responses consistent with the common misconception that the metal atoms and their cations are the same size. This is the next entry in Tables 6 and 7; for this analysis, students were given a score of “0” for the misconception that the sizes would be the same and a score of “1” if they said the atoms and ions would not be the same size. As we had expected, students who viewed animations showing transferred electrons as particles were less likely to say that the metals and cations were the same size (1.838/2) than students viewing animations showing transferred electrons as halos (1.568/2), $F(1, 142) = 6.157$, $p = 0.014$.

These results are consistent with previous research done using Sanger’s and Tasker’s animations (Cole, Rosenthal, & Sanger, 2019). In this previous study, students viewing Sanger’s animation (Figure 16a), which depicted transferred electrons as particles and did not use halos, were better able to recognize the relative sizes of silver atoms/silver ions and copper atoms/copper ions than students viewing Tasker’s animation that depicted the valence electrons as halos, similar to Figures 16b and 16d. This study also corroborates our prior assertion (Cole, Rosenthal, & Sanger, 2019) that students’ difficulties in answering questions related to atom and ion sizes after viewing Tasker’s animation stemmed from the way the valence electrons were depicted in this animation. Since both groups of students commented about how each animation depicted the atom/ion sizes, it does not appear that any difference in explanations from the two groups was based on a difference in selecting relevant images (Mayer, 2009) but instead was due to a difference in how the two groups interpreted and organized these selected images into their pictorial models. Although both methods of depicting the valence electrons can be viewed as accurate and defensible, these studies showed that students had fewer difficulties interpreting the images in terms of atom and ion sizes when the valence electrons were depicted as part of the atom's overall shape. However, it is entirely possible that the halo version of the atoms may be more helpful to students in explaining other behaviors of the atoms and ions.

Since showing or omitting ion charges did not affect how the relative sizes of the metal atoms and ions were depicted in these animations, we would not have expected there to be a significant effect on students' responses to these questions based on how the charges were depicted. These results suggest that adding or omitting the ions charges did not provide any useful or detrimental information that affected students' abilities to answer these questions related to atom and ion sizes.

Identifying the reaction's driving force. Student responses in identifying the reaction's driving force were not significantly different when ion charges were depicted or omitted in the animations ($F(1, 142) = 1.419$, $p = 0.236$) or when transferred electrons were depicted as particles or as halos in the animations ($F(1, 142) = 0.067$, $p = 0.796$). When we compared students' interpretations of Sanger's and Tasker's animations (Cole, Rosenthal, & Sanger, 2019), we found that students viewing Tasker's animation were more likely to incorrectly assume that water molecules or nitrate ions (if the students misinterpreted these water molecules as nitrate ions) were driving this reaction to occur, in part because they had misinterpreted the animation as suggesting that the water molecules were pulling the silver ions to the copper surface, and pulling copper(II) ions away from the copper surface (Cole, Rosenthal, & Sanger, 2019; Tasker, 2005; Tasker & Dalton, 2006). Since none of the animations in this study showed water molecules or nitrate ions directly interacting with any of the metal cations, none of these animations should be expected to affect students' explanations of the driving force for this reaction the way previous animations showing water molecules did.

Recognizing the 1:1 silver/nitrate ion ratio. Student recognition of the 1:1 silver/nitrate ion ratio before the reaction started also showed no significant difference when ion charges were depicted or omitted in the animations ($F(1,142) = 0.231$, $p = 0.631$) or when transferred electrons were depicted as particles or halos ($F(1, 142) = 0.240$, $p = 0.625$). All four animations in this study showed a 1:1 silver/nitrate ratio and were animated to have equal positive and negative charges in each screen shot. Since the number and type of cations and anions shown in each frame of the four animations used in this study were identical, there should be no reason to assume that changing how the charges or the transferred electrons were depicted would affect students' responses to this question.

Recognizing the 2:1 silver/copper ratio. As with the previous concept, there was no significant difference in student recognition of the 2:1 silver ion/copper atom reacting ratio when charges were depicted or omitted in the animations ($F(1, 142) = 0.001$, $p = 0.981$) or when the transferred electrons were depicted as particles or halos in the animations ($F(1, 142) = 0.094$, $p = 0.759$). All four animations in this study showed two silver ions reacting with one copper atom at the same time and at the same place on the copper surface. Since all four animations showed the oxidation-reduction reaction occurring in the same way, and happening at the same time and place, it makes sense that changing how the charges or the transferred electrons were depicted in the animations would not affect students' responses to this question.

Writing a balanced equation for the reaction. Students who viewed animations with the charges depicted were significantly better at writing the balanced equation for the silver nitrate – copper metal – reaction than students who viewed animations not depicting charges (13.195/20 for the students whose animations showed charges vs. 10.649/20 for students whose animations did not show charges, $F(1, 142) = 5.149$, $p = 0.025$). However, there was no significant difference in students' abilities to write the balanced equation for the reaction based on whether the transferred electrons were depicted as particles or halos ($F(1, 142) = 0.035$, $p = 0.851$). These results are consistent with student quotes from the interviews, which showed that most students started balancing the equations based on the charges of the atoms and ions in the equation. This focus on charges can even be seen in this student's attempts to balance the equation before viewing the animation, and the difficulty faced when this student couldn't remember the correct charges of one or more of the ions.

NC_EP Student: Ok, do I need to put the charges and subscripts down? Can't remember. Ag. I guess they are three-minus aren't they? Both of them three-minus? *Interviewers*: So what's the… Where… What are you having trouble with?

NC_EP Student: Just the charges on the stuff. So the solid forms would be neutral, I think, so.

Interviewers: Ok.

NC_EP Student: So, I guess …

Interviewers: So then the question… You're not really sure about the charge on silver or nitrate, copper or nitrate in the products?

NC_EP Student: Yeah. We'll call them neutral.

Interviewers: … we're kind of interested in your confidence. How confident are you about … that this [is] the right answer.

NC_EP Student: Ah, I'm really confident that this is the equation. As far as charges, I'm not sure at all.

This difficulty in writing the balanced equation if the charges of all species were not known also appeared to negatively impact some students who viewed animations without ion charges. In the following quote, the student is having difficulty identifying the charges of each species in the reaction. Although the student determined that the nitrate ions were negative and the silver ions were positive and used that to correctly explain that the silver ions were gaining one electron, the student incorrectly guessed the charge on the copper ion was two-minus, which made the charge of '$CuNO_3$' three-minus. The student recognized the charge imbalance and changed the charge of the copper metal to three-minus, even though the student was not confident with that change.

Interviewers: And now we're just interested if your balanced equation has changed.

NC_EP Student: I think it should. Well.

Interviewers: So why do you think it should change?

NC_EP Student: Because it's copper that's giving an electron. I don't think that's what we're showing though. Hmm. I feel like, um, maybe our signs aren't right. Like there should be a negative somewhere that's showing there's an electron being given up. So like…

Interviewers: What are the charges on each of the objects in your equation? What's the charge of nitrate?

NC_EP Student: Negative. So [the] silver [ion] would probably be positive.

Interviewers: So now does that help? What's happening to silver in this equation then?

NC_EP Student: It's gaining two electrons, so it be… No it's gaining one electron, so then it would be neutral. [Be] Cause it would be one-plus and then it's gaining a negative.

Interviewers: So then what about copper? So, in the copper nitrate what's the charge on copper then?

NC_EP Student: That would be … two-minus. Then, hmm… That means it's three-minus.

Interviewers: Oh, I see what you're saying, three-minus. So nitrate's minus-one …

NC_EP Student: Mm, hmm.

Interviewers: And a copper's minus-two …

NC_EP Student: Minus-two …

Interviewers: Then the total charge is minus-three.

NC_EP Student: Right.

Interviewers: Is that good, bad? Are we having issues, or?

NC_EP Student: Well, if it's minus-three here wouldn't it have to be minus-three on the left side as well in the reactant's side?

Interviewers: So what's the, what's the reactant's overall charge?

NC_EP Student: It's neutral, but then minus-three with the copper [metal] if you have a minus-three here.

Interviewers: Ok which … You're putting a minus-three on copper [metal] to balance the equation …

NC_EP Student: Yes.

Interviewers: Is that what copper … Is that what you think copper should have?

NC_EP Student: I'm not sure.

Interviewers: You're not sure. But you have to put it somewhere, right?

NC_EP Student: Yes. To balance it.

Interviewers: So you're not really sure. Ok. So, has the animation sort of changed your idea of the reaction?

NC_EP Student: Yes.

Interviewers: Um, has it made you more or less confident in your answer?

NC_EP Student: Less confident.

Students who viewed animations that showed the ion charges, on the other hand, had less difficulty in writing the balanced equation, and often mentioned the animation as being helpful in making any needed changes. The following quote shows that this student changed the formula for copper nitrate from $CuNO_3$ after viewing the chemical demonstration to $Cu(NO_3)_2$ after viewing the animation showing ion charges.

Interviewer: So how did your equation change?

WC_EP Student: Well we changed the equation of copper … nitrate

Interviewer: The formula for copper nitrate?

WC_EP Student: Yeah. We changed it because the NO_3 is a negative-one charge. And then ah, but copper (II) since it was …

Interviewer: The copper was plus-two?

WC_EP Student: Yeah. And that was like determined from the video.

Interviewer: Ok.

WC_EP Student: At least for me, but then like once, yeah, we changed it [copper nitrate formula to $Cu(NO_3)_2$] and the equation on the ah, like the products side we had to balance out the equation so it changed everything.

As with the concept involving the number of electrons transferred to silver ions from copper atoms in this reaction, students viewing animations showing ion charges were able to write a more accurate balanced equation for the overall oxidation-reduction reaction. This shouldn't be surprising, given that determining the chemical formulas of the reactants and products (based on atom and ion charges) seemed to be the starting point for many students when writing the overall equation for this reaction. In general, it appears that the animations showing ion charges provided students with relevant visual information (Mayer, 2009) needed to successfully determine the formulas of the ionic compounds in the reaction which helped these students in converting the particulate information presented by the animation into the symbolic formulas needed for the balanced equation (Johnstone, 2006, 2010). Unfortunately, students who viewed animations without ion charges were not given this relevant information and instead were forced to use their pre-existing domain-specific content knowledge regarding these charges (that may or may not be correct) to create these symbolic formulas as part of their balanced chemical equations (Lowe, 2014; Lowe & Boucheix, 2008).

Conclusions

In this study, we compared students' explanations of the silver nitrate-copper metal oxidation-reduction process after viewing a single animation that differed in how the ion charges and the transferred electrons were visually represented in these animations. In half of these animations, the ion charges were depicted with '+', '2+', and '–' signs; in the other half, these ion charges were completely omitted. Similarly, in half of these animations the transferred electrons were depicted as particles (red 'e^{-}' symbols) and in the other half the transferred electrons were depicted as a "halo of fuzziness" representing the valence electrons on the outside of the silver and copper metal atoms. While this study showed several significant main effects regarding how the ionic charges and the transferred electrons were depicted for the two variables (described in greater detail below), it was interesting to note that there were no interaction effects based on how students interpreted the two visual image choices (ion charges and transferred electrons) together. Although we had anticipated that there might be some interaction effects between these two variables, it appears that how the students interpreted one of these separate visual images was independent of their interpretations of the other visual image.

When ion charges were depicted in the animations, students were better at determining the number of electrons gained or lost by silver and copper and provided more accurate balanced chemical equations for the oxidation-reduction reaction compared to students viewing animations that did not show the ion charges. For these two concepts, it appears that the depiction of the ion charges in the animations provided relevant visual information that the students were able to use in constructing their pictorial models for these concepts. Student comments from the interviews showed that students were able to use the changes in the charges for the silver ions (+1 to neutral) and the copper atom (neutral to +2) to determine the number of electrons gained or lost by these species, and that students who were not shown these charges had more difficulty correctly determining the number of electrons gained or lost. The interview transcripts also demonstrated that, when writing the balanced chemical equation for this reaction, many students started with the charges of the silver and copper species before and after the reaction occurred to write the chemical formulas for the reactants and products in their balanced equations. It is also interesting to note that these students focused on the charges of the metal atoms and ions and not the number of electrons being transferred to silver from copper in order to write these equations.

When the transferred electrons in the animations were depicted as e^- particles, students provided more correct responses for how many electrons were gained or lost by silver and copper and for the relative sizes of the silver and copper atoms and their respective cations compared to students viewing animations using electron halos. With respect to the number of electrons transferred to each of the silver ions from the copper atoms, the student interview comments indicated that when the transferred electrons were depicted as particles the students could actually count the number of electrons being transferred, but when the animations depicted the transferred electrons as (non-qualitative) halos students had more difficulty determining the number of electrons gained or lost. With respect to determining the relative sizes of the metal atoms and ions, the animations depicting the transferred electrons as particles explicitly showed the sizes of the metal atoms/ions change but the animations depicting the transferred electrons as halos showed the atom/ion size changes by the addition or loss of the electron halos. The student interview quotes showed that some students had difficulty deciding whether the halos should be considered when determining the atom sizes, and this led more of the students viewing the electron halos to suggest that the metal atoms and ions would be the same size. This difficulty in interpreting the atom/ion sizes based on the presence or absence of the electron halos, and the misconception that the metal atom and cation sizes would be the same, is consistent with the student difficulties identified by our research group when comparing Sanger's and Tasker's animation of this same chemical reaction (Cole, Rosenthal, & Sanger, 2019; Rosenthal & Sanger, 2012, 2013a, 2013b).

Although this study found several significant differences in students' explanations based on how the charges and transferred electrons were depicted in the animations, their explanations for other aspects of the oxidation-reduction process were not affected by these visual depictions. Although the four animations used in this study differ in the way two key pieces of visual information are depicted, most of the visual images used in these four animations are identical. As such, questions that can be answered solely using the identical visual images in the four animations should show no differences in students' explanations based on the way the charges or the transferred electrons were depicted. For example, since the physical placement of the silver/copper atoms, the silver/copper ions, and the nitrate ions on the screens were identical for all four animations, it is not surprising that students' determination of the 1:1 Ag^+ to NO_3^- ratio and the 2:1 Ag^+/Cu reacting ratio were not affected by how the charges or transferred electrons were depicted in the animations. Similarly, we would not expect the students' explanations for the relative sizes of the metal atoms and ions to be affected by how the ion charges were depicted, since the atom/ion sizes were depicted the same regardless of whether the ions were depicted or omitted. A previous study from our research group using similar animations (Cole, Rosenthal, & Sanger, 2019) found that students' difficulties in determining the driving force of the reaction (and specifically, if water molecules or nitrate ions are driving this reaction) was based on how (and if) the water molecules were depicted in the animations. Since none of these four animations showed water molecules, we should expect similar student interpretations of water's or nitrate's role in driving this reaction. The non-significant differences in students' identification of the species being oxidized and reduced based on the depiction of the transferred electrons, on the other hand, was surprising given that these animations depicted the reactants and products of the oxidation-reduction reaction (silver and copper atoms, silver and copper(II) ions) very differently. Both depictions of the transferred electrons provided visual information that the students could use to determine which species was oxidized or reduced (the direction of e^- particle flow and size changes; the appearance or disappearance of electron halos). Based on the non-significant differences found in this study, it appears that students were equally successful in using these two very different sets of visual information to construct their pictorial models of the direction of electron transfer.

The superiority of the electron-particle images over the electron-halos and showing ion charges versus omitting them can be explained by Mayer's cognitive theory of learning (Mayer, 2009) and the animation processing model (Lowe and Boucheix, 2008; Lowe, 2014). According to Mayer's (2009) theory, which is based in part on cognitive load theory (Sweller, 1994; Sweller & Chandler, 1994), viewers of a non-narrated multimedia presentation can pay attention to and select only a part of the visual representation being shown due to the limited processing capacity of their working memory. In order to do this, viewers must judge which parts of a visual presentation represent relevant information that would help them to make sense of what has been viewed. Based on the results of this study, it appears that animations depicting the red electron-particles and the charges for the silver, copper(II), and nitrate ions provided students with more of the relevant information to correctly construct explanations of the oxidation-reduction process and the balanced equation for the reaction than the animations showing the electron-halo images or those omitting the ion charges. In the animation processing model (Lowe, 2014; Lowe & Boucheix, 2008), learners working to integrate internal mental models in space and time (Stage 3 of this model) are largely dependent on their own domain-specific knowledge to help them refine their mental model without misinterpreting information presented in the animation or focusing on irrelevant but flashy perceptual cues. Based on several students quotes described this study, it appears that some of the students were lacking basic chemistry facts (e.g., the correct charges of the silver, copper(II) and nitrate ions; the number of electrons gained by a silver ion or lost by a copper atom in this reaction; etc.) that were depicted in the animations showing ion charges or the electrons as particles that were not present in the animations that omitted ion charges or showed electrons as halos. As a result, students lacking these basic facts could learn them by viewing the animations showing ion charges or the electrons as particles but they were forced to use their (possibly faulty) existing domain-specific knowledge when viewing the animations omitting ion charges or showing electrons as halos.

Our research group has extensively studied how students interpreted the visual images depicted in different particulate-level animations showing the oxidation-reduction reaction of silver nitrate and copper metal (Cole, Rosenthal, & Sanger, 2019; Rosenthal & Sanger, 2012, 2013a, 2013b). In the first study described in the Cole, Rosenthal, and Sanger (2019) paper, we found that students' explanations for all aspects of the oxidation-reduction process were better for students viewing an animation that depicted the reaction in a more simplified two-dimensional manner than for students viewing an animation that depicted the reaction in a more complex and realistic manner. However, there were so many visual differences in the images used to depict this same reaction in the two animations that it became difficult to determine which of these differences were responsible for the differences in the students' explanations and which of these differences were largely irrelevant to the students' explanations of the depicted oxidation-reduction reaction. In order to address this limitation to that first study, our research group created a series of animations that differed from each other in the way these animations depicted only one or two key chemistry concepts. In the second study described in the Cole, Rosenthal, and Sanger (2019) paper, we found that showing or omitting water molecules in the silver nitrate solution of the animations had no effect on students' explanations of the oxidation-reduction process, but showing the water molecules confused some students into believing that the red-white water molecules were really nitrate ions. In this present study, we found that showing or omitting the ion charges on the silver, copper(II), and nitrate ions affected students' ability to determine how many electrons were being gained or lost by the silver ions and copper atom and also affected their ability to write a scientifically-accurate balanced equation for this reaction; we also found that showing the transferred electrons as discrete particles or as a non-qualitative halo on the metal atoms affected students' explanations regarding how many electrons were gained or lost by the silver ions and copper atom and the relative sizes of the silver and copper metal atoms and their respective cations. Based on these latest studies from our research group, we can conclude that of the many differences in the way the visual information was presented in the more simplified and the more complex animations used in first study of the Cole, Rosenthal, and Sanger (2019) paper, it appears that showing or omitting water molecules in the animations had little to no impact on students' explanations of the oxidation-reduction process but showing or omitting the ion charges and depicting the transferred electrons as particles or halos did appear to have a significant impact on these students' explanations of the oxidation-reduction process.

Future Studies. Although our research group has performed studies comparing animations that differ in how the visual images in these animations depict water molecules, ion charges, and transferred electrons, there are still other differences between Sanger's and Tasker's animations used in the Cole, Rosenthal, and Sanger (2019) paper that could be evaluated. These differences include the way the camera angle changes in the animations, the source and explanation of the blue color in solution, whether the oxidation and reduction half-reactions occur at the same place and time or in different spots and at different times. In addition, all of these studies from our research group have been performed using animations without narrations and it is possible that including narrations in these animations could lead to different research results. Although several theories of learning from visuals/multimedia (Baddeley, 1986; Paivio, 1986; Mayer, 2009) suggest that students will learn better with visual and verbal information (narrated animations) than from visual information alone (non-narrated animations), research by Jeung et al. (1997) found that if the cognitive load of selecting relevant visual images was high enough, the addition of written or spoken verbal information did not improve students' performance but if the cognitive load of selecting relevant visual images was relatively low, the addition of written or spoken verbal information did improve students' performance. Therefore, a study comparing students' explanations after viewing narrated versus non-narrated animations could shed some light on the extent of the cognitive load for selecting relevant images in these animations. Jueng et al. (1997) also noted that the use of visual cues could lower the effective cognitive load of selecting relevant visual images that would free up enough working memory for students to learn from the verbal narrations. Although we assumed that the use of visual cues in this study helped students select relevant visual images and that may have affected the mental pictorial model created by these students, this question can only be definitively answered by performing a study comparing students' performance after viewing animations that did or did not use visual cueing strategies. Finally, we observed that when students wrote a balanced chemical equation for a simple oxidation-reduction reaction, they started with the initial and final charges of the reactants and products instead of looking at the number of electrons transferred during the oxidation-reduction process. It might be interesting to replicate this study using different oxidation-reduction reactions in order to help instructors understand how students write these oxidation-reduction reactions and the types of difficulties these students encounter.

Conflicts of Interest

There are no conflicts to declare.

REFERENCES

Al-Balushi, S. M., Al-Musawi, A. S., Ambusaidi, A. K., & Al-Hajri, F. H. (2017). The effectiveness of interacting with scientific animations in chemistry using mobile devices on grade 12 students' spatial ability and scientific reasoning skills. *Journal of Science Education and Technology*, *26,* 70-81. doi: 10.1007/s10956-016-9652-2

Antonoglou, L. D., Charistos, N. D., & Sigalas, M. P. (2011). Design, development and implementation of a technology enhanced hybrid course on molecular symmetry: Students' outcomes and attitudes. *Chemistry Education Research and* P*ractice, 12*, 454-468. doi: 10.1039/C0RP90013C

Ardac, D., & Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching*, *41,* 317-337. doi: 10.1002/tea.20005

Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.

Brandriet, A. R., & Bretz, S. L. (2014). Measuring meta-ignorance through the lens of confidence: examining students' redox misconceptions about oxidation numbers, charge, and electron transfer. *Chemistry Education Research and Practice, 15,* 729-746, doi: 10.1039/c4rp00129j

Burrows, N. L., & Mooring, S. 4. (2015). Using concept mapping to uncover students' knowledge structures of chemical bonding concepts. *Chemistry Education Research and* P*ractice*, *16*, 53-66. doi: 10.1039/C4RP00180J

Cao, Y. (2005). Cueing strategies and instructional message design. In M. Simonson & M. Crawford (Eds.), *2005 Annual Proceedings-Orlando: Volume# 2* (pp. 131-142). Retrieved from http://s3.amazonaws.com/academia.edu.documents/25342056/ed499963.pdf?AWSAccessKeyId=AKIAJ56TQJRTWSMTNPEA&Expires 1484107091&Signature=V691w26YRLNYzL7XOEHa1OdARnE%3D&response-content disposition=inline%3B%20filename%3DLearning_to_collaborate_collaboratively.pdf#page=141

Clark, R. C., Nguyen, F., & Sweller, J. (2006). *Efficiency in learning: Evidence-based guidelines to manage cognitive load*. San Francisco: Pfeiffer.

Cole, M. H., Rosenthal, D. P., & Sanger, M. J. (2019). Two studies comparing students' explanations of an oxidation-reduction reaction after viewing a single computer animation: The effect of varying the complexity of visual images and depicting water molecules. *Chemistry Education Research and* P*ractice*. *20*, 738 –759. doi: 10.1039/c9rp00065h

Cook, M., Wiebe, E., & Carter, G. (2011). Comparing visual representations of DNA in two multimedia presentations. *Journal of Educational Multimedia and Hypermedia*, *20*, 21-42.

Davies, A. J. (1991). A model approach to teaching redox. *Education in Chemistry, 28*, 135-137.

De Jong, O., Acampo, J., & Verdonk, A. (1995). Problems in teaching the topic of redox reactions: Actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching, 32*, 1097-1110. doi: 10.1002/tea.3660321008

De Jong, O., & Treagust, D. F. (2002). The teaching and learning of electrochemistry. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, and J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 317-337). Dordecht: Kluwer

Garnett, P. J., Garnett, P., & Treagust, D. F. (1990). Implications of research on students' understanding of electrochemistry for improving science curricula and classroom practice. *International Journal of Science Education*, *12*, 147-156. doi: 10.1080/0950069900120203

Garnett, P. J., & Treagust, D. F. (1992a). Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching*, *29*, 121-149. doi: 10.1002/tea.3660290204

Garnett, P. J., & Treagust, D. F. (1992b). Conceptual difficulties experienced by senior high school students of electrochemistry: Electrochemical (galvanic) and electrolytic cells. *Journal of Research in Science Teaching*, *29*, 1079-1099. doi: 10.1002/tea.3660291006

Griffiths, A. K. (1994). A critical analysis and synthesis of research on students' chemistry misconceptions. In H. J. Schmidt (Ed.), *Proceedings of the 1994 international symposium on problem solving and misconceptions in chemistry and physics* (pp. 70-99). Hong Kong: International Council of Association for Science Education Publications

Gilbert, J. K., & Treagust, D. F. (2009). Towards a coherent model for macro, submicro, and symbolic representations in chemical education. In J. K. Gilbert & D. F. Treagust (Eds.), *Models and modeling in science education: Multiple representations in chemical education* (pp. 333-350). doi: 10.1007/978-1-4020-8872-8

Johnstone, A. H. (2006). Chemical education research in Glasgow in perspective. *Chemistry Education Research and Practice, 7*, 49-63. doi: 10.1039/B5RP90021B

Johnstone, A. H. (2010). You can’t get there from here. *Journal of Chemical Education*, *87*, 22-29. doi: 10.1021/ed800026d

Jueng, H-J., Chandler, P., & Sweller, J. (1997). The role of visual indicators in dual sensory mode instruction. *Educational Psychology*, *17*, 329-345. doi: 10.1080/0144341970170307

Kelly, R. M., Akaygun, S., Hansen, S. J. R., & Villalta-Cerdas, A. (2017). The effect that comparing molecular animations of varying accuracy has on students’ submicroscopic explanations. *Chemistry Education Research and* Practice, *18,* 582-600. doi: 10.1039/c6rp00240d

Kelly, R. M., & Jones, L. L. (2007). Exploring how different features of animations of sodium chloride dissolution affect students' explanations. *Journal of Science Education and Technology*, *85*, 303-309. doi: 10.1007/s10956-007-9065-3

Kelly, R. M., & Jones, L. L. (2008). Investigating students’ ability to transfer ideas learned from molecular animations to the dissolution process. *Journal of Chemical Education*, *85*, 303-309. doi: 10.1021/ed085p303

Lin, L. & Atkinson, R.K. (2011). Using animations and visual cueing to support learning of scientific concepts and processes. *Computers and Education*, *56*, 650-658. doi: 10.1016/j.compedu.2010.10.007

Loh, A. S. L., & Subramaniam, R. (2018). Mapping the knowledge structure exhibited by a cohort of students based on their understanding of how a galvanic cell produces energy. *Journal of Research in Science Teaching*, *55*, 777-809, doi: 10.1002/tea.21439

Lowe R. K. (2014). Dynamic visualizations: A two-edged sword? In W. Huang (Ed.), *Handbook of human centric visualization* (pp. 581---604). New York: Springer

Lowe R. K. and Boucheix J.- M., (2008), Learning from animated diagrams: How are mental models built? In G. Stapleton, J. Howse, and J. Lee (Eds.), *Diagrammatic representation and inference* (pp. 266-281). Berlin: Springer.

Lu, S., & Bi, H. (2016). Development of a measurement instrument to assess students' electrolyte conceptual understanding. *Chemistry Education Research and Practice, 17,* 1030-1040. doi: 10.1039/C6RP00137H

Lu, S., Bi, H., & Liu, X. (2018). The effects of explanation-driven inquiry on students' conceptual understanding of redox. *International Journal of Science Education, 40*, 1857-1873. doi: 10.1080/09500693.2018.1513670

Lu, S., Bi, H., & Liu, X. (2019). A phenomenographic study of 10th grade students' understanding of electrolytes. *Chemistry Education Research and Practice, 20,* 204-212. doi: 10.1039/C8RP00125A

Mayer, R. E. (2009). *Multi-media learning* (2nd ed.). Cambridge, UK: Cambridge University Press.

Ogude, N. A., & Braddley, J. D. (1996). Electrode processes and aspects relating to cell EMF, current, and cell components in operating electrochemical cells. *Journal of Chemical Education*, *73*, 1145-1149. doi: 10.1021/ed073p1145

Ozcelik, E., Karakus, T., Kursun, E., & Cagiltay, K. (2009). An eye-tracking study of how color coding affects multimedia learning. *Computers and Education*, *53*, 445-453. doi: 10.1016/j.compedu.2009.03.002

Özkaya, A. R. (2002). Conceptual difficulties experienced by prospective teachers in electrochemistry: Half-cell potential, and chemical and electrochemical equilibrium in galvanic cells. *Journal of Chemical Education*, *79*, 735-738. doi: 10.1021/ed079p735

Paivio, A., (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.

Patrick, M. D., Carter, G., & Wiebe, E. N. (2005). Visual representations of DNA replication: Middle grades students' perceptions and interpretations. *Journal of Science Education and Technology, 14,* 353-365. doi: 10.1007/s10956-005-7200-6

Qualtrics [software]. (2015). Provo, UT, USA: Qualtrics. Retrieved from http://www.qualtrics.com

Rosenthal, D. P., & Sanger, M. J. (2012). Student misinterpretations and misconceptions based on their explanations of two computer animations of varying complexity depicting the same oxidation-reduction reaction. *Chemistry Education Research and Practice*, *13*, 471-483. doi: 10.1039/c2rp20048a

Rosenthal, D. P., & Sanger, M. J. (2013a). How does the order of viewing two computer animations of the same oxidation-reduction reaction affect students' particulate-level explanations? In J. P. Suits & M. J. Sanger, (Eds.), *Pedagogic roles of animations and simulations in chemistry courses* (pp. 313-340). Washington, DC: American Chemical Society. doi: 10.1021/bk-2013-1142.ch013

Rosenthal, D. P., & Sanger, M. J. (2013b). How does viewing one computer animation affect students' interpretations of another animation depicting the same oxidation-reduction reaction? *Chemistry Education Research and Practice*, *14*, 286-296. doi: 10.1039/c3rp00006k

Russell, J. W., Kozma, R. B., Jones, T., Wykoff, J., Marx, N., & Davis, J. (1997). Use of simultaneous-synchronized macroscopic, microscopic, and symbolic representations to enhance the teaching and learning of chemical concepts. *Journal of Chemical Education*, *74*, 330-334. doi: 10.1021/ed074p330

Rutten, N., van Joolinger, W. R., & van der Veen, J. T. (2012). Learning effects of computer simulations in science education. *Computers & Education*, *58*, 136-153. doi: 10.1016/j.compedu.2011.07.017

Ryoo, K., Bedell, K., & Swearingen, A. (2018). Promoting linguistically diverse students' short-term and long-term understanding of chemical phenomena using visualizations. *Journal of Science Education and Technology*, *27*, 508-522. doi: 10.1007/s10956-018-9739-z

Sanger, M. J. (2009). Computer animations of chemical processes at the molecular level. In N. J. Pienta, M. M. Cooper, & T. J. Greenbowe (Eds.), *Chemist's guide to effective teaching, Vol. II* (pp. 198-211). Upper Saddle River, NJ: Prentice Hall.

Sanger, M. J., Brecheisen, D. M., & Hynek, B. M. (2001). Can computer animations affect college biology students' conceptions about diffusion & osmosis? *The American Biology Teacher*, *63*, 104-109. doi: 10.2307/4451051

Sanger, M. J., Campbell, E., Felker, J., & Spencer, C. (2007). "Concept learning versus problem solving": Does particle motion have an effect? *Journal of Chemical Education*, *84*, 875-879. doi: 10.1021/ed084p875

Sanger, M. J., & Greenbowe, T. J. (1997a). Common student misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells. *Journal of Research in Science Teaching*, *34*, 377-398. doi: 10.1002/(SICI)1098-2736(199704)34:4%3C377 ::AID-TEA7%3E3.0.CO;2-O

Sanger, M. J., & Greenbowe, T. J. (1997b). Students' misconceptions in electrochemistry: Current flow in electrolyte solutions and the salt bridge. *Journal of Chemical Education*, *74*, 819-823. doi: 10.1021/ed074p819

Sanger, M. J., & Greenbowe, T. J. (1999). An Analysis of College Chemistry Textbooks as Sources of Misconceptions and Errors in Electrochemistry. *Journal of Chemical Education*, *76*, 853-860. doi: 10.1021/ed076p853

Sanger, M. J., Phelps, A. J., & Fienhold, J. (2000). Using a computer animation to improve students' conceptual understanding of a can-crushing demonstration. *Journal of Chemical Education*, *77*, 1517-1520. doi: 10.1021/ed077p1517

Schmidt, H. –J., & Marohn, A., & Harrison, A. G. (2007). Factors that prevent learning in electrochemistry. *Journal of Research in Science Teaching*, *44*, 258-283. doi: 10.1002/tea.20118

Schnotz, W. & Rasch, T. (2005). Enabling, facilitating, and inhibiting effects of animations in multimedia learning: Why reduction of cognitive load can have negative results on learning. *Educational Technology Research and Development*, *53(3)*, 47-58. doi: 10.1007/BF02504797

Sirhan, G. (2007). Learning difficulties in chemistry: An overview. *The Journal of Turkish Science Education*, *4*, 2-20. doi: 10.1042/BJ20130599

Suits J. P. and Sanger M. J., (2013), Dynamic visualizations in chemistry courses, in Suits J. P. and Sanger M. J. (ed.), Pedagogic Roles of Animations and Simulations, ACS Symposium Series, Washington DC: American Chemical Society, vol. 1142, pp. 1–13. doi**:** 10.1021/bk-2013-1142.ch001

Supasorn, S. (2015). Grade 12 students' conceptual understanding and mental models of galvanic cells before and after learning by using small-scale experiments in conjunction with a model kit. *Chemistry Education Research and Practice*, *16*, 393-407. doi: 10.1039/C4RP00247D

Sweller J. (1994). Cognitive load theory, learning difficulty and instructional design, *Learning Instruction.*, *4*, 295-312.

Sweller, J. (1999). *Instructional design in technical areas*. Camberwell, Australia: ACER Press.

Sweller J. and Chandler P. (1994). Why some material is difficult to learn, *Cognition and. Instruction*, *12*, 185-233.

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry "triplet". *International Journal of Science Education*, *33*(2), 179-195. doi: 10.1080/09500690903386435

Tasker, R. (2005). Using multimedia to visualize the molecular world: Educational theory into practice. In N. J. Pienta, M. M. Cooper, & T. J. Greenbowe (Eds.), *Chemist's guide to effective teaching, Vol. I* (pp. 195-211). Upper Saddle River, NJ: Prentice Hall.

Tasker, R. & Dalton, R. (2006). Research into practice: Visualisation of the molecular world using animations. *Chemistry Education Research and Practice*, *7*, 141-159. doi: 10.1039/b5rp90020d

Thomas, G. P. (2017). 'Triangulation': An expression for stimulating metacognitive reflection regarding the use of 'triplet' representations for chemistry learning. *Chemistry Education Research and Practice, 18*, 533-548. doi: 10.1039/C6RP00227G

Tsaparlis, G. (2018). Teaching and learning electrochemistry. *Israel Journal of Chemistry*, *58,* 1-16. doi: 10.1002/ijch.201800071

Williamson, V. M. & 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. doi: 10.1002/tea.3660320508

Williamson, V. M., Lane, S. M., Gilbreath, T., Tasker, R., Ashkenazi, G., Williamson, K. C., & Macfarlane, R. D. (2012). The effect of viewing order of macroscopic and particulate visualizations on students' particulate explanations. *Journal of Chemical Education*, *89,* 979-987. doi: 10.1021/ed100828x

Williamson, V. M., Watkins, J. T., & Williamson III, K. C. (2013). The effect of student-constructed animations versus storyboards on students' mental rotation ability, equilibrium content knowledge, and attitudes. In J. P. Suits & M. J. Sanger, (Eds.), P*edagogic roles of animations and simulations in chemistry courses* (pp. 293-311). Washington, DC: American Chemical Society. doi: 10.1021/bk-2013-1142.ch012

CHAPTER 4: SUMMARY

The water molecules study (Chapter 2) and the ion charges and transferred electrons study (Chapter 3) were designed to answer a number of key research questions (Figure 18) about the effect of adding information deemed to be extraneous or relevant by chemical education experts (myself and the chemical education researchers on this committee) to an animation of an oxidation-reduction reaction on students' conceptual understanding of that process.

Water molecules study

1. How does viewing a computer animation that shows or omits water molecules affect students' conceptual understanding of the oxidation-reduction process depicted in these animations?
2. After viewing both animations, what do students think are the important differences between how the two animations depict visual information regarding the oxidation-reduction process?
3. After viewing both animations, which animations do the students believe should be used in the future to teach students about the oxidation-reduction reaction depicted in these animations?

Ion charges and transferred electrons study

1. Does labeling or omitting the charges of all ions in the animation (silver, copper(II), nitrate ions) affect students' ability to explain the oxidation-reduction process?
2. Does depicting the electrons being transferred from copper atoms to silver ions as 'e–' particles or as a fuzzy cloud or halo affect students' ability to explain the oxidation-reduction processes?
3. Is there an interaction effect between the way the ion charges and the transferred electrons are depicted on students' explanations of the oxidation-reduction process?

Figure 18. The research questions addressed in this dissertation.

Water Molecules Study

In order to determine the answers to the three research questions in the water molecules study, students' explanations of the oxidation-reduction reaction occurring between aqueous silver nitrate and solid copper metal were compared after viewing a chemical demonstration and a particulate-level animation of the reaction either showing or omitting water molecules and the potentially extraneous information associated with the movement and behavior of these molecules. The results of this study showed that students' conceptual understanding of the oxidation-reduction process depicted in these animations did not differ for the two groups of students for most topics, including the presence of ion pairs in solution, the electron transfer process, recognizing the 1:1 ratio of silver ion and nitrate ion, recognizing the 2:1 reacting ratio of silver ions and copper atoms, and writing a balanced equation for the reaction. In fact, students' responses from the two groups only differed when attempting to identify how the nitrate ion was depicted in the animation. Students viewing the animation showing water molecules had more difficulty correctly identifying the nitrate ions than those viewing the animation without water molecules. Specifically, many students who saw the water molecules in their animation misidentified them as nitrate ions. The water molecules were depicted as a red sphere with two white spheres and the nitrate ions were depicted as a blue sphere with three red spheres and a negative charge. Because the animation showing water molecules had the entire background filled with red-and-white water molecules, this visually dense depiction showing so many water molecules might have suggested to students that the red-and-white objects were very important in the reaction and this might have convinced them that they were really the nitrate ions. The presence of so many red-white molecules may also have obscured the relatively few blue-red nitrate ions in the animation and distracted or confused the students as they attempted to find and identify the nitrate ions.

The water molecules study also examined whether or not there was an order effect on students' interpretations of the animations when students viewed the same two animations in a different order. In contrast to the Rosenthal and Sanger studies (Cole, Rosenthal & Sanger, 2019; Rosenthal & Sanger, 2013a, 2013b), which found significant effects when students viewed the same two animations created by different animators in a different order, I found no significant order effects for any of the concepts in the water molecules study. One of the questions in the water molecules study asked: 'Why does this reaction happen?' (the driving force of the reaction). Analysis of the students' explanations of this concept resulted in four categories for the driving force: Electronegativity differences (the scientifically accepted answer), stability (ΔG), nitrate ions as the driving force, and other miscellaneous explanations. Even though there was no significant order effect for the correct responses to this question, there was a significant order effect for one of the *incorrect* responses (nitrate ions as the driving force). Students who viewed the animation showing water molecules first and then the animation with water molecules omitted did not change their beliefs about nitrate's role in this reaction. However, students who viewed the animation with water molecules omitted first were more likely to suggest nitrates were driving the reaction after subsequently viewing the animation with water molecules shown. It is possible that the visually dense moving background in the animation showing the water molecules might have confused these students into misinterpreting the red-white molecules as nitrate ions and interpreting their behavior and motions as suggesting that the nitrate ions were driving this reaction to occur. Tasker and Dalton (2006) also noted that students misinterpreted the animated behaviors and motions of water molecules in their animations, and this caused students to incorrectly identify the water molecules as driving the chemical reactions to occur. Based on the results of the water molecules study, I have concluded that the addition of the water molecules to the animation represented a seductive detail (Mayer, 2009) that distracted/confused some of the students into incorrectly identifying the nitrate ions and interpreting the behaviors and motions of the red-white "nitrate ions" as driving the reaction. The misidentification of the nitrate ions and the misinterpretation of the nitrate ions as the driving force of the reaction may be explained as the result of an overload in the students' working memory. This can happen when the extraneous information (added water molecules) in a computer animation increases the cognitive load of the learning event involving the animation to a point where the learner may not have enough working memory available to deal with the intrinsic cognitive load of the lesson.

The only difference between the two animations in the water molecules study identified by students was the absence or presence of water molecules. However, student comments were divided as to whether showing or omitting water molecules in the animation would be more useful to future students. Some students preferred the animation without water molecules because it was less confusing and distracting. Although more students suggested that instructors should show the animation without water molecules to future students, when given a choice as to which animation(s) they would show in class, the majority of students indicated that both animations should be shown. The students reasoned that the two animations shown together would provide a more complete picture of the aqueous silver nitrate – copper metal oxidation-reduction reaction at the particulate level and they believed that future students could learn from both animations. It is interesting to note that Kelly et al. (2017), who compared a scientifically inaccurate animation and a scientifically accurate animation, also found that students thought that using both animations would enhance the learning of future students.

The water molecules study suggests that showing or omitting water molecules in the animation of the aqueous silver nitrate – copper metal oxidation-reduction reaction did not affect students' abilities to explain the oxidation-reduction process. Based on the results of this study, it appears that animators can choose to show or omit water molecules in aqueous solutions without dramatically affecting students' explanations of the oxidation-reduction process.

Ion Charges and Transferred Electrons Study

To answer the three research questions in the ion charges and transferred electrons study (Figure 18), students' explanations of the silver nitrate-copper metal oxidation-reduction process were compared after viewing a videotaped demonstration of the reaction followed by one of four animations that differed in how the ion charges and the transferred electrons were visually represented. The two animations that explicitly labeled ion charges differed in how the transferred electrons were depicted. In one animation the transferred electrons were depicted red ‘e^-‘ symbols and in the other animation the transferred electrons were depicted as a “halo of fuzziness” representing the valence electrons on the outside of the silver and copper metal atoms (Figures 1a and 1b). The other two animations that did not explicitly label ion charges also differed in how the transferred electrons were depicted as described above (Figures 1c and 1d).

Analysis of the data showed that students who viewed the animations depicting ion charges were better at determining the number of electrons gained or lost in the reaction and provided a more accurate balanced equation for the oxidation-reduction reaction than those who viewed the animations that did not show ion charges. Based on these results, I concluded that depicting of the ion charges in the animations provided relevant visual information that the students used to construct their pictorial models for these concepts. Similarly, students who viewed the animations that depicted transferred electrons as e^- particles were better able to correctly determine how many electrons were gained or lost by silver and copper as well as the relative sizes of the silver and copper atoms and their respective cations than students viewing the animations using electron halos. The major advantage of depicting transferred electrons as particles is that it explicitly tells students *how many* electrons are transferred from one chemical to another; depicting electrons as halos shows the direction of electron flow but does *not* tell how many electrons are transferred. The superiority of showing ion charges and depicting transferred electrons as particles can be explained by Mayer's cognitive theory of learning (Mayer, 2009) and the animation processing model (Lowe, 2014; Lowe & Boucheix, 2008). Mayer (2009) posited that viewers of non-narrated multimedia presentations can pay attention to and select only a part of the visual representations being shown due to limited processing capacity of the working memory. While doing this, viewers must choose which images of the visual presentation represent relevant information that will help them make sense of what has been viewed. The animations depicting ion charges and transferred electrons as particles appeared to provide students with more relevant information, allowing them to correctly construct more complete explanations of the oxidation-reduction process and the balanced equation for the reaction than students viewing the animations omitting ion charges or those showing transferred electrons as halos. According to the animation processing model (Lowe, 2014; Lowe & Boucheix, 2008), learners working to integrate internal mental models in space and time are largely dependent on their own domain-specific knowledge to help them refine their mental model without misinterpreting information presented in the animation or focusing on irrelevant but flashy perceptual cues. Student comments elicited in this study indicated that some of the students were lacking basic chemistry information (e.g., the correct charges of the silver, copper(II) and nitrate ions; the number of electrons gained by a silver ion or lost by a copper atom in this reaction; etc.) that was depicted in the animations showing ion charges and the transferred electrons as particles that was not found in the animations that omitted ion charges or showed electrons as halos. The results of this study demonstrated that students lacking this basic chemistry knowledge could find it by viewing the animations that explicitly labeled ion charges or depicted the electrons as particles and provide better explanations; however, those students viewing the animations omitting ion charges and depicting transferred electrons as halos were forced to use their existing (and possibly faulty) domain-specific knowledge to explain the oxidation-reduction processes in their explanations.

Many of the remaining oxidation-reduction concepts examined in this study showed no significant difference in students' explanations based on which animations the students viewed. Since most of the visual information presented in the four animations in this study was identical except for the two key concepts, the questions that could be answered using visual images that were identical in the four animations should show no difference in students' explanations. Additionally, since there were no interaction effects between the visual images, I concluded that how students interpreted the two visual image choices (ion charges and transferred electrons) were independent of one another.

In the ion charges and transferred electrons study, it is evident that the animations that labeled ion charges and depicted transferred electrons were more effective in helping students who viewed these animations better explain some of the processes in the oxidation-reduction reaction depicted in these animations as well as write a more correct balanced chemical equation. When symbolic cues are used in animations of particulate behavior, they provide students with visually relevant information that enables them to form a more realistic pictorial model of the concept being displayed in the animation.

Limitations and Future Studies

One limitation in the studies presented in Chapters 2 and 3 of this dissertation was that students viewed animations of an oxidation-reduction reaction without narration. Narration was excluded from these studies because they were based on the Rosenthal and Sanger studies (2012, 2013a, 2013b), which used the more complex animation (Figure 1b) and the simple animation (Figure 1a) without narration. Jeung, et al. (1997) discovered that if the cognitive load of selecting relevant images was high enough, adding written or spoken verbal information did not improve student performance. He and his coworkers also noted that if the cognitive load of selecting relevant images was relatively low, however, the addition of written or spoken verbal information could improve student performance. Since I did not determine whether the cognitive load of selecting relevant images was high or low for the animations used these studies and Mayer (2009), Pavio (1986), and Baddeley (1986) all suggest that students learn better from multimedia presentations when they are accompanied by narration, then there is a possibility that including narration with these animations could lead to different results. Therefore, a study comparing students' explanations of the oxidation-reduction process after viewing narrated animations or comparing narrated versus non-narrated animations might prove useful in determining the cognitive load for selecting relevant images in these animations. In both the water molecules study and the ionic charge and transferred electrons study, the animations contained visual cues such as the yellow flashes behind each electron transfer event between the copper atoms and the two silver ions. The use of visual cues could lower the cognitive load of selecting relevant visual images, freeing up enough working memory for students to learn from verbal narration. It should be kept in mind that any narration accompanying an animation should focus on and explain the relevant information (scaffolding) and reduce the effects of extraneous information depicted by that animation.

Showing water molecules in our animations had limited impact on student understanding of the oxidation-reduction process occurring in the animation. The only effect that showing water molecules had was to affect the ability of some students to correctly identify the red-white objects as water molecules and not nitrate ions. This was likely due to the overwhelming visual information depicted in the background of the animation that made it difficult to distinguish between the water molecules and nitrate ions. If the water molecules animation was redesigned so that it contained fewer visible water molecules, students' explanations of the oxidation-reduction process could be compared after viewing the animation showing fewer water molecules versus the animation completely omitting water molecules.

These studies also showed that when students wrote balanced equations for a simple oxidation-reduction reaction, they started with the initial and final charges of the reactants and products instead of looking at the number of electrons transferred during the reaction. In order to help instructors understand how students write oxidation-reduction reactions and the types of difficulties they encounter, it might be useful to replicate the ion charges and transferred electrons study using different oxidation-reduction reactions and perhaps non oxidation-reduction reactions as well.

REFERENCES

Akaygun, S. (2016). Is the oxygen atom static or dynamic? the effect of generating animations on students' mental models of atomic structure. *Chemistry Education Research and Practice*, *17,* 788-807. doi: 10.1039/c6rp00067c

Andersson, B. (1986). Pupils' explanations of some aspects of chemical reactions. *Science Education*, *70,* 549-563. doi: 10.1002/sce.3730700508

Appleton, K. (1989). A learning model for science education. *Research in Science Education*, *19*, 13-24. doi: 10.1007/BF02356842

Appleton, K. (1993). Using theory to guide practice: Teaching science from a constructivist perspective. *School Science and Mathematics*, *93*(5), 269-274. doi: 10.1111/j.1949-8594.1993.tb12242.x

Ausubel, D. P. Novak, J. D. & Hanesian, H. (1978). *Educational psychology: A cognitive view*. London: Holt, Rinehart and Winston.

Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.

Ben-Zvi, R., Eylon, B. S., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63,* 64-66. doi: 10.1021/ed063p64

Berney, S. & Betrancourt, M. (2016). Does animation enhance learning? A meta-analysis. *Computers & Education*, *101*, 150-167. doi: 10.1016/j.compedu. 2016.06.005

Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education*, *63,* 873-877. doi: 0.1021/ed063p873

Boo, H. K. (1998). Students' understandings of chemical bonds and the energetics of chemical reactions. *Journal of Research in Science Teaching*, *35,* 569-581. doi: 10.1002/(SICI)1098-2736(199805)35:5<569::AID-TEA6>3.0.CO;2-N

Brandriet, A.R. (2014). *Investigating students' understandings of the symbolic, macroscopic, and particulate domains of oxidation-reduction and the development of the redox concept* (Doctor dissertation, Miami University). Retrieved from http://rave.ohiolink.edu/etdc/view?acc_num=miami1403694253

Brandriet, A. R. & Bretz, S. L. (2014a). Measuring meta-ignorance through the lens of confidence: examining students' redox misconceptions about oxidation numbers, charge, and electron transfer. *Chemistry Education Research and Practice*, *15,* 729-746. doi: 10.1039/C4RP00129J

Brandriet, A. R. & Bretz, S. L. (2014b). The development of the redox concept inventory as a measure of students' symbolic and particulate redox understandings and confidence. *Journal of Chemical Education*, *91*, 1132-1144. doi: 10.1021/ed500051n

Bussey, T. J., Orgill, M. K., & Crippen, K. J., (2013). Variation theory: A theory of learning and a useful theoretical framework for chemical education research. *Chemistry Education Research and Practice*, *14*, 9-22. doi: 10.1039/c2rp20145c

Bunce, D. M. (2001). Does Piaget have anything to say to chemists? *Journal of Chemical Education*, *78*, 1107. doi: 10.1021/ed078p1107.2

Cardak, O. (2009). Science students' misconceptions of the water cycle according to their drawings. *Journal of Applied Science*, *9*, 865-873. doi: 10.3923/jas.2009.865.873

Carlson, R., Chandler, P., & Sweller, J. (2003). Learning and understanding science instructional material. *Journal of Educational Psychology*, *95*, 629-640.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive Models of Science: Minnesota Studies in the Philosophy of Science* (129-186). Minneapolis, MN: University of Minnesota Press. Retrieved from http://philpapers.org/rec/CHICCW

Chi, M. T. H., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence* (pp. 7–75). Hillsdale, NJ: Erlbaum.

Chi, M. T. H., & Roscoe, R. D. (2002). The processes and challenges of conceptual change. In L. Margarita and L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 3-27). Netherlands: Kluwer Academic Publishers.

Claxton. G. (1990). *Teaching to learn: A direction for education*. London: Cassell.

Cole, M. H., Rosenthal, D. P., & Sanger, M. J. (2019). Two studies comparing students' explanations of an oxidation-reduction reaction after viewing a single computer animation: The effect of varying the complexity of visual images and depicting water molecules. *Chemistry Education Research and Practice*, *20*, 738 -759 doi: 10.1039/c9rp00065h

Copper, M., & Klymkowsky, M. (2013). Chemistry, life, the universe, and everything: A new approach to general chemistry, and a model for curriculum reform. *Journal of Chemical Education*, *90*, 1116-1122. doi: 10.1021/ed300456y

Creswell, J. W. (2003). *Research design: Qualitative, quantitative, and mixed methods approaches*. Thousand Oaks, CA: Sage Publications, Inc.

Davidowitz, B., Chittleborough, G., & Murray, E. (2010). Student-generated submicro diagrams: A useful tool for teaching and learning chemical equations and stiochiometry. *Chemistry Education Research and Practice*, *11*, 154-164. doi: 10.1039/c005464j

De Jong, O., Acampo, J., & Verdonk, A. (1995). Problems in teaching the topic of redox reactions: Actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching*, *32*, 1097-1110. doi: 10.1002/tea.3660321008

Dwyer, F. M. (1972). The effect of overt responses in improving visually programmed science instruction. *Journal of Research in Science Teaching*, *9*, 47-55. doi:

Ebenezer, J. V., & Erickson, G. L. (1996). Chemistry students’ conceptions of solubility: A phenomenography. *Science Education*, *80*, 181-201. doi: 10.1002/(SICI)1098-237X(199604)80:2<181::AID-SCE4>3.0.CO;2-C

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look into the future. *Journal of Chemical Education*, *76*, 548-554. doi: 10.1021/ed076p548

Garner, R., Gillingham, M. G., & White, C. S. (1989). Effects of “seductive details” on macroprocessing and microprocessing in adults and children. *Cognition and Instruction*, *6*, 41-57. doi: 10.1207/s1532690xci0601_2

Garnett, P. J. & Treagust, D. F. (1992a). Conceptual difficulties experienced by senior high schools students of electrochemistry: Electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching*, *29*, 121-142. doi: 10.1002/tea.3660290204

Garnett, P. J., & Treagust, D. F. (1992b). Conceptual difficulties experienced by senior high school students of electrochemistry: Electrochemical (galvanic) and electrolytic cells. *Journal of Research in Science Teaching*, *29*, 1079-1099. doi: 10.1002/tea.3660291006

Gilbert, J. K. & Treagust, D. (Ed.), (2009). *Multiple representations in chemical education*. Dordrecht: Springer-Verlag.

Greenbowe, T. J. (1994). An interactive multimedia software program for exploring electrochemical cells. *Journal of Chemical Education*, *71*, 555-557. doi: 10.1021/ed071p555

Harp, S. F., & Maslich, A. A. (2005). The consequences of including seductive details during lecture. *Teaching of Psychology, 32,* 100-103. doi: 10.1207/s15328023top3202_4

Herron, J. D. (1975). Piaget for chemists. Explaining what "good" students cannot understand. *Journal of Chemical Education, 52*, 146-150. doi: 10.1021/ed052p146

Höffler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction, 17,* 722-738. doi: 10.1016/j.learninstruc.2007.09.013

Inhelder, B. & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York: Basic Books.

Johnson, P. (1998). Progression in children's understanding of a 'basic' particle theory: A longitudinal study. *International Journal of Science Education*, *20,* 393-412. doi: 10.1080/0950069980200402

Johnstone, A. H., (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education*, *70*, 701-705. doi: 10.1021/ed070p701

Johnstone, A. H. (2006). Chemical education research in Glasgow in perspective. *Chemistry Education Research and Practice, 7,* 49-63. doi: 10.1039/B5RP90021B

Johnstone, A. H. (2010). You can't get there from here. *Journal of Chemical Education*, *87,* 22-29. doi: 10.1021/ed800026d

Jueng, H-J., Chandler, P., & Sweller, J. (1997). The role of visual indicators in dual sensory mode instruction. *Educational Psychology*, *17*, 329-345. doi: 10.1080/0144341970170307

Kelly, R. M. (2014). Using variation theory with metacognitive monitoring to develop insights into how students learn from molecular visualizations. *Journal of Chemical Education*, *91*, 1152-1161. doi: 10.1021/ed500182g

Kelly, R. M., Akaygun, S., Hansen, S. J. R., & Villalta-Cerdas, A. (2017). The effect that comparing molecular animations of varying accuracy has on students' submicroscopic explanations. *Chemistry Education Research and Practice, 18,* 582-600. doi: 10.1039/c6rp00240d

Kelly, R. M. & Jones, L. L. (2008). Investigating students' ability to transfer ideas learned from molecular animations to the dissolution process. *Journal of Chemical Education, 85*, 303-309. doi: 10.1021/ed085p303

Kelly, R. M., Phelps, A. J., & Sanger, M. J. (2004). The effects of a computer animation on students' conceptual understanding of a can-crushing demonstration at the macroscopic, microscopic, and symbolic levels. *Chemical Educator, 9*, 184-189. doi: 10.1333/s00897040779a

Kirschner, P. A., Kirschner, F., & Paas, F. (2008). Cognitive learning theory. *Psychology of Classroom Learning*, *1*, 205-209. Retrieved from http://lnx-hrl-075v.web.pwo.ou.nl/bitstream/1820/2328/1/Cognitive_Load_Theory%20-%20Psychology%20of%20Classroom%20Learning.pdf

Kozma, R. B., Chin, E., Russell, J. & Marx, N. (2000). The role of representations and tools in the chemistry laboratory and their implications for chemistry instruction. *Journal of the Learning Sciences*, *9*, 105-143. Retrieved from http://www.jstor.org.ezproxy.mtsu.edu/stable/1466853?seq=1#page_scan_tab_contents

Kozma, R. B. & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*, 949-968. doi: 10.1002/(SICI)1098-2736(199711)34:9<949::AID-TEA7>3.0.CO;2-U

Loh, A. S. L., & Subramaniam, R. (2018). Mapping the knowledge structure exhibited by a cohort of students based on their understanding of how a galvanic cell produces energy. *Journal of Research in Science Teaching*, *55*, 777-809, doi: 10.1002/tea.21439

Lowe, R. K. (2003). Animation and learning: Selective processing of information in dynamic graphics. *Learning and Instruction*, *13*, 157-176. doi: 10.1016/S0959-4752(02)00018-X

Lowe, R. K. (2004). Animation and learning: Value for money? In R. Atkinson, C. McBeath, D. Jonas-Dwyer & R. Phillips (Eds), Beyond the comfort zone: Proceedings of the 21st ASCILITE Conference (pp. 558-561). Perth, 5-8 December. Retrieved from http://www.ascilite.org.au/conferences/perth04/procs/lowe-r.html

Lowe, R. K. (2014). Dynamic visualizations: A two-edged sword?, in W. Huang (ed.), *Handbook of human centric visualization*, New York: Springer, pp. 581-604.

Lowe, R. K., & Boucheix, J.- M. (2016). Principled animation design improves comprehension of complex dynamics. *Learning and Instruction, 45,* 72-84. doi: 10.1016/j.learninstruc.2016.06.005

Lowe, R. K., & Boucheix, J.- M. (2008). Learning from animated diagrams: How are mental models built?, in G. Stapleton, J. Howse, and J. Lee (eds.), *Diagrammatic representation and inference*, Berlin: Springer, pp. 266-281.

Lu, S., & Bi, H. (2016). Development of a measurement instrument to assess students' electrolyte conceptual understanding. *Chemistry Education Research and Practice, 17,* 1030-1040. doi: 10.1039/C6RP00137H

Lu, S., Bi, H., & Liu, X. (2018). The effects of explanation-driven inquiry on students' conceptual understanding of redox. *International Journal of Science Education, 40,* 1857-1873. doi: 10.1080/09500693.2018.1513670

Lu, S., Bi, H., & Liu, X. (2019). A phenomenographic study of 10th grade students' understanding of electrolytes. *Chemistry Education Research and Practice, 20,* 204-212. doi: 10.1039/C8RP00125A

Mayer, K. (2010). Addressing students' misconceptions about gases, mass, and composition. *Journal of Chemical Education, 88,* 111-115. doi: 10.1021/ed1005085

Mayer, R. E. (2001). *Multi-media learning* (1st ed.). Cambridge, UK: Cambridge University Press.

Mayer, R. E. (2009). *Multi-media learning*. (2nd ed.). Cambridge, UK: Cambridge University Press.

Mayer, R. E., & Moreno, R. (2002). Animations as an aid to multimedia learning. *Education Psychology Review*. *14,* 87-99. Retrieved from http://www.jstor.org/stable/23363490

Mulford, D. R. & Robinson, W. R. (2002). An inventory for alternate conceptions among first-semester general chemistry students. *Journal Chemical Education, 79,* 739-744. doi: 10.1021/ed079p739

Naah, B. M., & Sanger, M. J. (2012). Student misconceptions in writing balanced equations for dissolving ionic compounds in water. *Chemical Education Research and Practice, 13*, 186-194. doi: 10.1039/c2rp00015f

Nurrenbern, S. C. (2001). Piaget's theory of intellectual development revisited. *Journal of Chemical Education, 78*, 1107. doi: 10.1021/ed078p1107.1

Nurrenbern, S. C., & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education*, *64*, 508-510. doi: 10.1021/ed064p508

Nyachwaya, J. M. (2016). General chemistry students' conceptual understanding and language fluency: Acid-base neutralization and conductometry. *Chemistry Education Research and* P*ractice, 17*, 509-522. doi: 10.1039/C6RP00015K

Österlund, L. -L., Berg, A., & Ekborg, M. (2010). Oxidation-reduction models in chemistry textbooks for the upper secondary school: Friend or foe? *Chemistry Education Research and Practice, 11*, 182-192. doi: 10.1039/C005467B

Özkaya, A. R. (2002). Conceptual difficulties experienced by prospective teachers in electrochemistry: Half-cell potentials, cell potential, and chemical and electrochemical equilibrium in galvanic cells. *Journal of Chemical Education*, *79*, 735-738. doi: 10.1021/ed079p735

Paivio, A., (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.

Piaget, J. & Cook, M. T. (1952). *The origins of intelligence in children*. New York, NY: International University Press.

Prybil, J. R. & Bodner, G. M. (1987). Spatial ability and its role in organic chemistry: A study of four organic courses. *Journal of Research in Science Teaching, 24,* 229-240. doi: 10.1002/tea.3660240304

Rosenthal, D. P. & Sanger, M. J. (2012). Student misinterpretations and misconceptions based on their explanations of two computer animations of varying complexity depicting the same oxidation-reduction reaction. *Chemistry Education Research and Practice, 13*, 471-483. doi: 10.1039/c2rp20048a

Rosenthal, D. P. & Sanger, M. J. (2013a). How does the order of viewing two computer animations of the same oxidation-reduction reaction affect students' particulate-level explanations? In Suits J.P. & Sanger, M.J. (Eds.), *Pedagogic roles of animations and simulations in chemistry courses* (pp. 313-340). Washington, DC: American Chemical Society. doi: 10.1021/bk-2013-1142.ch013

Rosenthal, D. P. & Sanger, M. J. (2013b). How does viewing one computer animation affect students' interpretations of another animation depicting the same oxidation-reduction reaction? *Chemistry Education Research and Practice*, *14*, 286-296. doi: 10.1039/c3rp00006k

Rutten, N., van Joolinger, W. R., & van der Veen, J. T. (2012). Learning effects of computer simulations in science education. *Computers & Education*, *58,* 136-153. doi: 10.1016/j.compedu.2011.07.017

Sanger, M. J. (2005). Evaluating students' conceptual understandings of balanced equations and stiochiometric ratios using a particulate drawing. *Journal of Chemical Education*, *82*, 131-134. doi: 10.1021/ed082p131

Sanger, M. J., Brecheisen, D. M., & Hynek, B. M. (2001). Can computer animations affect college biology students' conceptions about diffusion and osmosis? *American Biology Teacher*, *63*, 104-109. doi: 10.1662/0002-7685(2001)063[0104:CCAACB]2.0.CO;2

Sanger, M. J., Campbell, E., Felker, J., & Spencer, C. (2007). "Concept learning versus problem solving": Does particle motion have an effect? *Journal of Chemical Education*, *84,* 875-879. doi: 10.1021/ed084p875

Sanger, M. J. & Greenbowe, T. J. (1997a). Common student misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells. *Journal of Research in Science Teaching*, *34,* 377-398. doi: 10.1002/(SICI)1098-2736(199704)34:4<377::AID-TEA7>3.0.CO;2-O

Sanger, M. J. & Greenbowe, T. J. (1997b). Students' misconceptions in electrochemistry: Current flow in electrolyte solutions and the salt bridge. *Journal of Chemical Education*, *74*, 819-823. doi: 10.1021/ed074p819

Sanger, M. J. & Greenbowe, T. J. (1999). An analysis of college chemistry textbooks as sources of misconceptions and errors in electrochemistry. *Journal of Chemical Education*, *76,* 853-860. doi: 10.1021/ed076p853

Sanger, M. J., Phelps, A. J., & Fienhold, J. (2000). Using a computer animation to improve students' conceptual understanding of a can-crushing demonstration. *Journal of Chemical Education*, *77,* 1517-1520. doi: 10.1021/ed077p1517

Schmidt, H. –J., & Marohn, A., & Harrison, A. G. (2007). Factors that prevent learning in electrochemistry. *Journal of Research in Science Teaching, 44*, 258-283. doi: 10.1002/tea.20118

Schmidt, H. -J. & Volke, D. (2003). Shift of meaning and students' alternative concepts. *International Journal of Science Instruction*, *25*, 1409-1424. doi: 10.1080/0950069022000038240

Sirhan, G. (2007). Learning difficulties in chemistry: An overview. *The Journal of Turkish Science Education*, *4*, 2-20. doi: 10.1042/BJ20130599

Smith, K. C. & Nakhleh, M. B. (2011). University students' conceptions of bonding and melting and dissolving phenomena. *Chemistry Education Research and Practice*, *12*, 398-408. doi: 10.1039/C1RP90048J

Suits, J. P. (2015). Design of dynamic visualizations to enhance conceptual understanding in chemistry courses. In Garcia-Martinez, J. & Serrano-Torregrosa, E. (Eds.), *Chemical Education: Best Practices, Opportunities, and Trends* (pp. 595-616). Weinheim: Wiley-VCH.

Suits, J. P. & Sanger, M. J. (2013). Dynamic visualizations in chemistry courses. In Suits, J. P. & Sanger, M. J. (Eds.), *Pedagogic Roles of Animations and Simulations in Chemistry Courses* (pp. 1-13). Washington, DC: American Chemical Society.

Supasorn, S. (2015). Grade 12 students' conceptual understanding and mental models of galvanic cells before and after learning by using small-scale experiments in conjunction with a model kit. *Chemistry Education Research and Practice*, *16*, 393-407. doi: 10.1039/C4RP00247D

Sweller J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction.*, *4*, 295-312. doi: 10.1016/0959-4752(94)90003-5

Sweller, J., & Chandler, P. (1994), Why some material is difficult to learn. *Cognition and Instruction*, *12*, 185-233. Retrieved from https://www-jstor-org.ezproxy.mtsu.edu/stable/pdf/3233760.pdf

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry "triplet". *International Journal of Science Education*, *33*(2), 179-195. doi: 10.1080/09500690903386435

Tasker, R. & Dalton, R. (2006). Research into practice: Visualisation of the molecular world using animations. *Chemistry Education Research and Practice*, *7*, 141-159. doi: 10.1039/b5rp90020d

Treagust, D. F., Chandrasegaran, A. L., Zain, A. N. M., Ong, E. T., Karpudewan, M., & Halim, L. (2011). Evaluation of an intervention instructional program to facilitate understanding of basic particle concepts among students enrolled in several levels of study. *Chemistry Education Research and Practice*, *12*, 251-261. doi: 10.1039/c1rp90030g

Tsaparlis, G. J. (1997). Atomic and molecular structure in chemical education: A critical analysis from various perspectives of science education. *Journal of Chemical Education*, *74*, 922-925. doi: 10.1021/ed074p922

Tsaparlis, G. (2018). Teaching and learning electrochemistry. *Israel Journal of Chemistry*, *58*, 1-16. doi: 10.1002/ijch.201800071

Visualization. (n.d.). In *Vocabulary.com dictionary*. Retrieved December 5, 2019, from https://www.vocabulary.com/dictionary/visualization

von Glasersfeld, E. (1980). The concept of equilibration in a constructivist theory of knowledge. In F. Beneseler, P. M. Hejl, W. K. Köck (Eds.), *Autopoiesis, communication, and society: The theory of autopoietic system in the social sciences* (pp. 75-85). New York: Campus Verlag.

Wadsworth, B. J. (2004). *Piaget's theory of cognitive and affective development: Foundations of constructivism*. New York, NY: Longman Publishing Group.

Williamson, V. (2008). The particulate nature of matter: An example of how theory-based research can impact the field. In D. Bunce & R. S. Cole (Eds.), *Nuts and bolts of chemical education research* (pp. 67–78). Washington, DC: American Chemical Society.

Williamson, V. M. (2011). Teaching chemistry with visualizations: What's the research evidence? In Bunce, D. (Ed.), *Investigating classroom myths through research on teaching and learning* (pp. 65-81). Washington, DC: American Chemical Society.

Williamson, V. M. & 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. doi: 10.1002/tea.3660320508

Wu, H. & Shah, P. (2004). Exploring visuospatial thinking in chemistry education. *Science Education*, *88*, 465-492. doi: 10.1002/sce.10126

Yang, E. M., Andre, T., Greenbowe, T. J., & Tibbel, L. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education*, *25*, 329-349. doi: 10.1080/09500690210126784

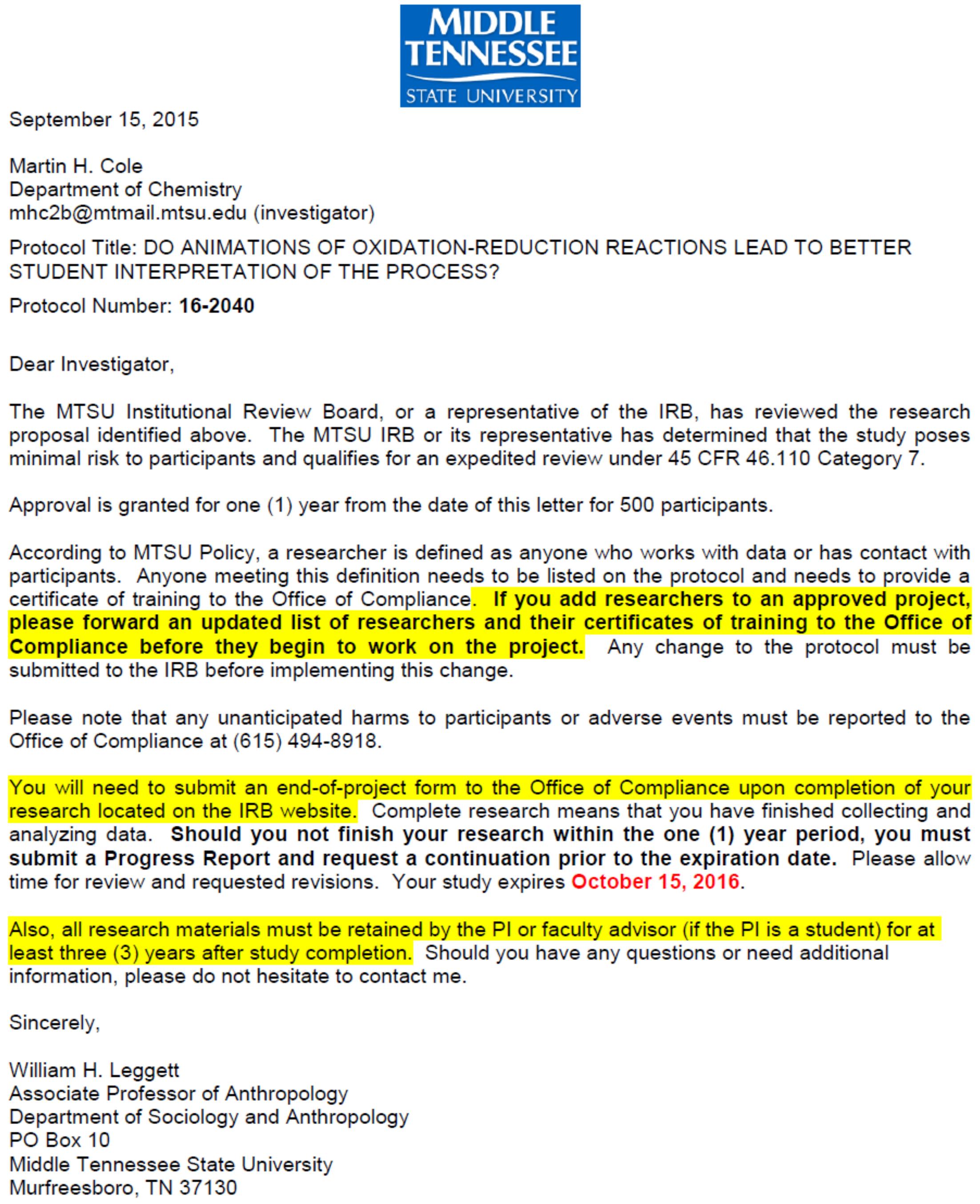
Yarroch, W. L. (1985). Student understanding of chemical equation balancing. *Journal of Research in Science Teaching*, *22*, 449-459. doi: 10.1002/tea.3660220507

Yaseen, Z. (2018). Using student-generated animations: the challenge of dynamic chemical models in states of matter and the invisibility of the particles. *Chemistry Education Research and Practice*, *19*, 1166-1185. doi: 10.1039/C8RP00136G

APPENDICES

APPENDIX A

Institutional Review Board (IRB) Approval Letter



MIDDLE TENNESSEE
STATE UNIVERSITY

September 15, 2015

Martin H. Cole
Department of Chemistry
mhc2b@mtmail.mtsu.edu (investigator)

Protocol Title: DO ANIMATIONS OF OXIDATION-REDUCTION REACTIONS LEAD TO BETTER STUDENT INTERPRETATION OF THE PROCESS?

Protocol Number: **16-2040**

Dear Investigator,

The MTSU Institutional Review Board, or a representative of the IRB, has reviewed the research proposal identified above. The MTSU IRB or its representative has determined that the study poses minimal risk to participants and qualifies for an expedited review under 45 CFR 46.110 Category 7.

Approval is granted for one (1) year from the date of this letter for 500 participants.

According to MTSU Policy, a researcher is defined as anyone who works with data or has contact with participants. Anyone meeting this definition needs to be listed on the protocol and needs to provide a certificate of training to the Office of Compliance. **If you add researchers to an approved project, please forward an updated list of researchers and their certificates of training to the Office of Compliance before they begin to work on the project.** Any change to the protocol must be submitted to the IRB before implementing this change.

Please note that any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918.

You will need to submit an end-of-project form to the Office of Compliance upon completion of your research located on the IRB website. Complete research means that you have finished collecting and analyzing data. **Should you not finish your research within the one (1) year period, you must submit a Progress Report and request a continuation prior to the expiration date.** Please allow time for review and requested revisions. Your study expires **October 15, 2016**.

Also, all research materials must be retained by the PI or faculty advisor (if the PI is a student) for at least three (3) years after study completion. Should you have any questions or need additional information, please do not hesitate to contact me.

Sincerely,

William H. Leggett
Associate Professor of Anthropology
Department of Sociology and Anthropology
PO Box 10
Middle Tennessee State University
Murfreesboro, TN 37130

APPENDIX B

USE of the REDOX CONCEPT INVENTORY

In an attempt to determine if the interventions used in the two studies presented in this dissertation (Chapters 2 and 3) were effective, I decided to use the Redox Concept Inventory (ROXCI). The ROXCI is an 18-item inventory developed by Brandriet and Bretz (2014a, 2014b) to measure students' understanding and confidence in their understanding of the oxidation-reduction process. The advantage of using the ROXCI in my studies is that it was evaluated for validity and reliability by Brandriet and Bretz (2014a, 2014b) using first- and second-semester general chemistry students.

Based on the information described in these papers, ROXCI appeared to be the ideal instrument to determine whether students in my studies improved their understanding of the oxidation-reduction process after viewing the various animations depicting the oxidation-reduction reaction of aqueous silver nitrate and solid copper metal. I contacted Dr. Stacey Lowery Bretz from the Miami University of Ohio via e-mail and asked for permission to use the ROXCI in my studies. Dr. Bretz replied back with a set of conditions regarding the use of the ROXCI (see Appendix C) and upon agreeing to those conditions I was sent a copy of the ROXCI.

The ROXCI was administered to the participants using paper versions of the ROXCI inventory after the students had received classroom instruction on oxidation-reduction reactions (for first-semester general chemistry students) or electrochemistry (for second-semester general chemistry students) but before viewing the video of the chemical demonstration and then again after the students had viewed the animations depicting the oxidation-reduction process and completed the Qualtrics survey. Since the ROXCI was not intended to be in the public domain, the actual test could not placed into the online Qualtrics survey developed for these studies. However, an answer sheet for the students to complete was placed into the Qualtrics survey. The paper copies of the ROXCI questionnaires were each assigned a number. Under my supervision, the numbered copies of the ROXCI were handed out to the participants. The Qualtrics survey asked the participants to record the number of their ROXCI questionnaire and place an answer for each question of the inventory into the Qualtrics answer sheet within the Qualtrics survey. When the participants were finished they returned the numbered copy of the ROXCI to me.

Unfortunately, although I found several significant differences between the students' explanations of the oxidation-reduction process in research studies described in Chapters 2 and 3, I did not find any significant differences in the students' scores for the ROXCI concept inventory. For the water molecules study (Chapter 2), the one-way ANOVA for the overall ROXCI scores of the two groups yielded an $F(1,72)$ value of 0.442 ($p = 0.508$). The average ROXCI score for the students viewing the animation with water molecules was 4.54/18 (standard error of 0.40) while the average ROXCI score for the students viewing the animation without water molecules was 4.95 (standard error of 0.46). For the ion charges and transferred electron study (Chapter 3), the two-way ANOVA for the overall ROXCI scores for the four groups had a main effect of $F(1,144) = 2.587$ ($p = 0.110$) for the ion charges, a main effect of $F(1,144) = 0.046$ ($p = 0.831$) for the transferred electrons, and an interaction effect of $F(1,144) = 0.210$ ($p = 0.648$) for the two variables. Students viewing the animation with ion charges and with electron particles had an average ROXCI score of 4.95 (standard error = 0.46), students viewing the animation with ion charges and with electron halos had an average ROXCI score of 5.25 (standard error = 0.56), students viewing the animation without ion charges and with electron particles had an average ROXCI score of 4.43 (standard error = 0.36), and students viewing the animation without ion charges and with electron halos had an average ROXCI score of 4.31 (standard error = 0.41).

As can be seen from these ANOVA calculations, none of the probability values (*p*) for these comparisons were less than 0.05 and therefore, I could not conclude that the students in any of the subgroups within either study had performed differently on the ROXCI inventory. As a result, the ROXCI could not be used to explain any differences identified in the students' explanations of the oxidation-reduction reaction in the water molecules study or the ion charges and transferred electron study. Therefore my major professor and I decided not to report the results of the ROXCI in Chapters 2 and 3. It is possible that, if I had had more students involved in this study (larger sample size), that there may have been significant differences among the overall ROXCI scores for the students in each subgroup of both studies, and then the ROXCI scores might have been useful in explaining the differences in the responses from the different subgroups.

I would like to thank Dr. Alexandra Brandriet and Dr. Stacey Lowery Bretz from the Miami University of Ohio for giving me permission to use the ROXCI in my studies (see Appendix C).

APPENDIX C

Permission to Use the Redox Concept Inventory (ROXCI)

Dear Martin,

Thank you for your interest in using the Redox Concept Inventory (ROXCI). It is available for you to use. Here are our policies regarding its use:

- It takes years of development effort to create and validate a reliable assessment instrument.
- No item, nor the whole concept inventory, is to be incorporated into a web-based question delivery system without adequate security to prevent printing or other unauthorized access by students.
- Please do not allow any student to keep a copy of the concept inventory. Please do not post any of the questions on the internet.
- If the instrument, or any individual question, is released to the public domain, students will locate it and all our work will be for naught. In fact, you might not want to use the formal name of the test on the versions you have students take.

If your intended use conforms with these policies, please let me know and I will reply with a copy of the instrument as well as an answer key.

Again, thank you very much for your interest in our research.

Sincerely,
Stacey

Stacey Lowery Bretz • Volwiler Distinguished Research Professor

Miami University • Department of Chemistry & Biochemistry • Oxford, OH 45056

513.529.3731 • bretzsl@miamioh.edu • http://chemistry.miamioh.edu/bretzsl

APPENDIX D

Permission to Use A Learning Model for Science Education (Figure 2)

This Agreement between Martin Cole ("You") and John Wiley and Sons ("John Wiley and Sons") consists of your license details and the terms and conditions provided by John Wiley and Sons and Copyright Clearance Center.

License Number	4632201350964
License date	Jul 18, 2019
Licensed Content Publisher	John Wiley and Sons
Licensed Content Publication	School Science and Mathematics
Licensed Content Title	Using Theory to Guide Practice: Teaching Science From a Constructivist Perspective
Licensed Content Author	Ken Appleton
Licensed Content Date	Mar 17, 2010
Licensed Content Pages	10
Type of use	Dissertation/Thesis
Requestor type	University/Academic
Format	Print and electronic
Portion	Figure/table
Number of figures/tables	1
Original Wiley figure/table number(s)	Figure 1
Will you be translating?	No
Title of your thesis / dissertation	The Effect of Adding Relevant and Irrelevant Visual Images to an Animation of an Oxidation-Reduction Reaction on Students’ Conceptual Understanding
Expected completion date	Aug 2019
Expected size (number of pages)	190