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Learning from contrasting molecular animations with a metacognitive monitor activity

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Animations;
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Abstract A common problem associated with having General Chemistry students view animations is that students tend to accept the animations as ''correct'' explanations without question or consideration for their limitations. This study proposes a new strategy for presenting animations in chemistry instruction that requires students to critique contrasting animations to determine which animation is a best fit with video-recorded scientific evidence. The purpose of the study was to examine how undergraduate students, enrolled in their first semester of a General Chemistry course, responded to two contrasting animations, one that was scientifically accurate and one that was scientifically inaccurate, as molecular level explanations of a video of a redox reaction involving the reaction between solid copper and aqueous silver nitrate. An analysis of a metacognitive monitoring activity was performed to study how students saw similarities and differences between the animations, as well as, to their own molecular level explanations of the reaction event. The findings revealed that students picked up on the mechanistic differences between the animations, but they struggled with understanding why the reaction happened. Regardless of their background knowledge of chemistry, students voiced preference for animations that were simplistic in their appearance and obvious in what they conveyed while also having an explicit connection to the macroscopic level.

PALABRAS CLAVE
Animaciones;
Química universitaria;
Metacognición;
Ideas de los estudiantes

Aprender de las animaciones de contraste molecular con una actividad de monitorización metacognitiva

Resumen Los estudiantes de Química General tienden a concebir las animaciones de fenómenos químicos como explicaciones «correctas» sin cuestionar sus limitaciones. Este estudio presenta una nueva estrategia para presentar animaciones en clases de química que demanda que los estudiantes critiquen animaciones contrastantes con el fin de determinar cuál de ellas representa mejor la evidencia científica presentada en un video. El propósito de la investigación

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fue el determinar cómo estudiantes de licenciatura en el primer semestre de un curso de Química General respondían a 2 animaciones contrastantes, una de ellas representando de manera científicamente adecuada la reacción redox entre cobre sólido y una solución de nitrato de plata y otra representando el mismo fenómeno de manera inadecuada. Se llevó a cabo un análisis de una actividad de monitorización metacognitiva para estudiar las diferencias y similitudes detectadas por los estudiantes entre las 2 animaciones, así como su propia explicación a nivel molecular del fenómeno observado. Los resultados revelan que los estudiantes fueron capaces de detectar diferencias mecánicas entre las 2 animaciones, pero tuvieron problemas para entender por qué ocurre la reacción. Independientemente de sus conocimientos de química, los estudiantes expresaron preferencia por las animaciones más simplistas y con conexiones explícitas con el nivel macroscópico.

Introduction

When we learn, often times we get things wrong. Many of us would acknowledge that it is normal to have errors in understanding as it is a natural part of the learning process. Unfortunately, repairing inaccuracies in understanding by showing or telling students the correct answers has had limited success. For example, in several animation studies, researchers have found that when students were shown animations and then attempted to draw or explain their new understanding, alternative perceptions persisted (Kelly & Akaygun, 2016; Kelly & Jones, 2007, 2008; Kelly, 2014; Rosenthal & Sanger, 2012, 2013; Ryoo & Linn, 2014; Tasker & Dalton, 2006) and uneven learning was observed. Finding ways to instill deep and meaningful reflection of the information presented in animations has proven challenging. Some researchers have partnered animations with video demonstrations and laboratory activities to bridge better understanding of the relationship between macroscopic and submicroscopic levels (Velázquez-Marcano, Williamson, Ashkenazi, Tasker, & Williamson, 2004) while others have focused on scaffolding animations with guidance and cartoon tutors to assist students in making sense of the animations (Kelly & Akaygun, 2016). But none have intentionally designed visualizations that animate reaction mechanisms incorrectly so that they can be placed in opposition to more accurate animations to challenge students to critique the animations to determine which animation is best, until this study.

Dynamic molecular visualizations

Dynamic visualizations have been investigated quite vigorously in the field of chemistry education for their assistance in improving the viewers' learning of scientific phenomena (Kelly & Jones, 2007, 2008; Kelly & Akaygun, 2016; Kelly, 2014; Kozma & Russell, 1997; Marbach-Ad, Rotbain, & Stavy, 2008; Plass, Homer, & Hayward, 2009; Rosenthal & Sanger, 2012, 2013; Sanger & Greenbowe, 2000; Sanger, Phelps, & Fienhold, 2000). Visualizations explicitly depict unseen processes, such as chemical reactions in order to help learners understand the movement and interactions that are believed to take place (Ardac & Akaygun, 2004; Kozma & Russell, 1997; Ryoo & Linn, 2014; Tasker & Dalton, 2006). However, molecular structures and dynamic processes can be complicated and different representations of the same structure are used by chemists for different purposes. They can also be used by instructors and researchers to emphasize different features (Jones, 2013; Rosenthal & Sanger, 2012, 2013). Kelly and Jones (2007) studied how the features of two different styles of visualizations, affected students' explanations of how sodium chloride dissolves. One of the animations focused meticulously on the dynamics and energetics of the solution process and also showed the lattice to be made of moving ions that vibrated in their lattice positions. While the other animation simplified the look of the solvent and focused on how the water molecules extracted unmoving ions in the sodium chloride lattice. The mix of using both animations improved students' understanding of the functional nature with which water molecules attracted ions and drew them away from the salt lattice; however, learning was uneven and several students retained misconceptions about the nature of salt dissolution and some developed new misconceptions.

Complicated visualizations, while seemingly more scientifically accurate than simplistic animations, have been noted to potentially interfere with student learning (Rosenthal & Sanger, 2012; Ryoo & Linn, 2014). Students can become confused by what they see and have difficulty interpreting complex animations which can prevent them from fully understanding the scientific phenomenon (Mayer, 2001; Rosenthal & Sanger, 2012; Ryoo & Linn, 2014). In contrast, animations that are too simplistic can sometimes influence students to reduce the amount of details they portray in their oral and drawn explanations (Kelly, 2014). The kinds of visualization attributes students recognize as varying from their understanding are typically general characteristics such as structural features and very basic movements. Students expend less attentional effort on detailed features, such as the vibrational movement of ions in a lattice or the complex network of water molecules functioning as a solvent in an aqueous salt solution (Kelly, 2014). In general, animations can help students better understand dynamic molecular processes and researchers should be encouraged to investigate mixing different types of visualizations (Jones, 2013).

Redox animations

In the early 1990s the *VisChem* project under the leadership of Roy Tasker produced a suite of scientifically accurate molecular animations depicting the structures of substances and select chemical and physical changes. One of Tasker's animations, most relevant to this study because it is used as our most scientifically accurate animation, illustrated the reduction of silver ions to silver atoms on a growing crystal while also showing the release of copper(II) ions into solution. The animation was unique because its goal was to depict how the silver dendrites were able to form by accounting for the movement of electrons across several copper atoms to reach the silver ion. Tasker and Dalton (2006), found that when students were shown animations and practiced drawing representations of the molecular level there was a significant increase in the number of scientifically acceptable features students expressed in their drawings. Students demonstrated long-term recall of VisChem animations and some of their subjects expressed that the animations helped them picture the molecular level throughout their academic undergraduate studies. Thus the animation by itself was considered a very useful educational tool; however, learning was somewhat uneven leaving room to study how multiple animations might assist in helping students understand the nature of this reaction.

Rosenthal and Sanger (2012, 2013) conducted a pair of studies examining how students responded to two animations: The VisChem redox animation, without its narration, and a more simplistic animation of the same reaction event designed by Michael J. Sanger. In the first study (2012), they examined the misinterpretations and misconceptions that students developed from the dual animation viewing experience. They contend that students had more difficulty interpreting the more complex animation and that students may have misinterpreted information depicted in the animations. The most pervasive misinterpretation was noted when students viewed the VisChem animation. Students confused the red/white shapes of water molecules as the nitrate ions. Rosenthal and Sanger reported that ''students viewing the more simplified animation provided better explanations for eight different concepts related to the oxidation–reduction reaction compared to the students viewing the more complex animation.'' Rosenthal and Sanger (2013) also investigated how viewing the VisChem animation prior to the Sanger animation and vice versa affected their participants' explanations of the animations. They concluded that viewing the more complicated animation (VisChem) did not appear to have an effect on the participants' explanations of the information depicted by the more simplistic animation (Sanger), but viewing the simplified animation prior to the more complex animation had an effect on students' explanations. They observed that students who viewed the simplistic animation first, better understood the stoichiometric ratios, electron transfer process and how the equation was balanced. However, it negatively impacted students' explanations of the source of the blue color in the aqueous solution. While these studies examined how students learned from two styles of animations, both animations were considered scientifically acceptable and students were not challenged to critique the animations for flaws. Our study introduces students to the limitations of models and examines how students must come to terms with determining which animation best represents the reaction phenomenon.

Prior knowledge and metacognitive monitoring

According to Chi (2008) instructors should consider three conditions in regard to learners' prior knowledge, skills, beliefs and concepts when they prepare their instruction or show students animations. First, a learner may have no prior knowledge of the scientific concepts that are being shown in the animation although they may have related knowledge. In this situation, Chi describes that the prior knowledge is missing. In order to learn the new concept, the learner is basically adding new knowledge. Second, a learner may have incomplete understanding of a concept and learning can be thought of as filling in the gaps. Finally, a learner may have garnered conceptions that are in conflict with to-be-learned concepts and these misconceptions must be corrected. In the case of the knowledge that is misconceived, Chi contends that beliefs or single ideas have the greatest likelihood of undergoing revision when the false belief is confronted either explicitly or implicitly with correct information that contradicts and refutes the false belief. In this case, showing students animations may be enough to achieve conceptual change. However, typically animations represent more complicated phenomena for which a learner must draw together a collection of beliefs in the form of a mental model. ''A mental model is an internal representation of a concept, or an interrelated system of concepts that correspond to the external structure that it represents'' (Clement & Vosniadou, 2008; Nersessian, 2008 as cited by Halverson & Tran, 2016). According to Chi (2008), flawed mental models can be transformed when the false components of the model are refuted by instruction and recognized by learners as contradictions. However, Chi points out that revising some false beliefs or learning more accurate conceptions does not guarantee successful transformation of a flawed mental model as students may find logical ways of retaining their false beliefs. In this study, animations with different mechanisms were presented to students to instill contradiction. We examine how students responded to the animations and how it affected students' understanding through a metacognitive monitoring exercise.

Metacognitive monitoring is a detection strategy that this study employs to examine how students make sense of the contrasting treatment animations in comparison to their own comprehension of the reaction event. Metacognition refers to the knowledge and experiences that assist learners to understand and monitor their cognitive processes (Flavell, 1979; Schraw, Crippen, & Hartley, 2006) Metacognition includes two main subcomponents: knowledge of cognition or what we know about our cognition and regulation of cognition or how we plan, monitor and evaluate our understanding (Schraw et al., 2006). Metacognition plays an important role in helping students construct and refine their mental models or psychological representations of scientific phenomenon, because through this intervention students self-regulate how their learning is progressing and adapt to fit with other models or ways of thinking. Metacognitive monitoring is a strategy that an individual performs to control cognitive activities and to ensure that cognitive goals are met (Mathabathe & Potgieter, 2014). Monitoring enables individuals to observe, reflect on or experience their own cognitive processes (Flavell, 1979 as cited in Mathabathe & Potgieter, 2014). In monitoring, students may be asked to make judgements about their memory, knowledge, learning or comprehension. Sometimes students may construct flawed representations that may affect their ability to fully understand scientific concepts. In such cases, the question of how to assist students to correct their understanding involves some degree of conceptual change and to elicit this change often requires some degree of intellectual conflict or cognitive disequilibrium.

Methods

Theoretical framework: variation theory

The framework used to guide this research was variation theory, a phenomenographic theoretical framework. ''The objective of phenomenographic research is to identify and describe the variation in experiences or perceptions that a particular group of people has of a given phenomenon.'' (Orgill, 2007 as cited in Bussey, Orgill, & Crippen, 2013). This use of variation theory as a framework has been used by Kelly (2014) and Kelly and Akaygun (2016) in previous visualization research and has been an effective lens through which to investigate how students experience a phenomenon, because it focuses on the details that students determine to be salient in constructing new understanding as identified through students' oral and drawn explanations. In this study, the experience was two animations that portrayed different reaction mechanisms for the same redox reaction presented to the students through a video. The VisChem animation depicted the electron exchange that occurs between copper atoms and silver ions resulting in copper(II) ions being drawn into solution through hydration and crystalline silver forming at the surface of the copper. From this point forward the VisChem animation will be referred to as the Electron Exchange Animation (EEA) because that is the mechanism that it highlights. The second animation was constructed by Kelly and her animation artist, Mina Evans, to have features, such as the copper lattice and the silver and nitrate ions that were similar to the EEA, but this animation showed two silver nitrate molecules colliding with the copper surface, releasing the nitrate ions, which then bonded to a copper atom and went into solution. Thus the animation focuses on a physical mechanism that of silver nitrates colliding and then trading a silver atom for a copper atom (the animation does not distinguish whether these atoms are ions) and from this point forward this animation will be referred to as the Physical Exchange Animation (PEA). Since the variation theory lens suggests that a student's experience of the phenomenon depends on the particular features to which they attend, each student was asked to generate lists of the 'key features' they noticed in each animation, as well as a list of the 'key features' they represented in their molecular level drawings of the reaction made prior to seeing the animations. Then the aim was to examine how students described the variation between the lists of key features through the metacognitive monitoring activity.

Participants and study design

The study reported in this manuscript was part of a larger study that involved seventeen students who were enrolled in their first semester of General Chemistry, in the fall of 2014, at a midsized university in the Western United States. The treatment occurred in the second half of the semester after the students had completed labs on conductivity of aqueous solutions for constructing net ionic equations, a mystery solution lab on precipitation, and a lab on the activity series of metals. They had also learned about redox reactions and had learned to balance complex redox reactions through the half-reaction method. It is noted that the researcher was not the instructor of the course and thus unable to describe students' experience learning the submicroscopic nature of the reactions.

The goal of this study was to examine how these students learned from a treatment in which they were presented with two contrasting animations in which they were specifically tasked with determining which animation was most scientifically accurate based on its fit with experimental evidence presented in a video according to the following sequence (Fig. 1). First, the students viewed a video of an experiment in which copper wire was added to three test tubes filled with pure water, aqueous silver nitrate and aqueous copper (II) nitrate. After 13 min passed, the wires were removed. The test tube that contained aqueous silver nitrate was the only solution that reacted with the wire causing a gray build-up on the wire and the solution changed from colorless to blue. In addition to the reaction, all three solutions were tested for electrical conductance prior to and after the reaction. Only the aqueous salt solutions were found to conduct electricity to the same level before and after the reaction. The students were asked to make note of three key pieces of evidence involving the redox reaction between the aqueous silver nitrate and the copper wire: the build-up on the wire, the electrical conductivity results taken before and after the reaction and the noticeable blue color of the solution and they were invited to draw their atomic level pictures of the reaction, at the start of the reaction, after 8 min had lapsed and after the wire was removed and the reaction had stopped. They then constructed a list of the key features they conveyed in their pictorial representations and orally described them. Next, the students were instructed very clearly that they would be shown two animations that could contain flaws and their job was to critique the animations for accuracy and fit with the experimental evidence observed in the video. Then the students viewed one of two animations and they performed a metacognitive monitoring exercise in which they hand wrote a list of the key features of the animation to identify what the student focused on when viewing the animation. They were then asked to compare and contrast their list of features for their hand drawn explanation to the features in the animation by marking the features that were similar to and different from each other with different pen colors. The students then orally described

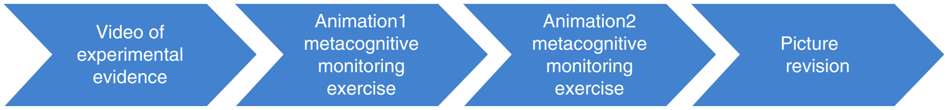

Figure 1 Sequence of events involved in the study.

what they marked and why. Next, the students viewed the remaining animation following the same procedures they did for the first. The study ended with a revision task, in which students were asked to redraw the atomic level of the three stages of the reaction as they now understood the reaction. The students orally described their drawings and explained why they made any changes. The students were also asked which animation they felt best represented the reaction event and why.

Of the seventeen participants, seven students fell into two extreme groups: one group, composed of three students (1 female and 2 males) revised their drawn and oral explanations to fit nearly exclusively with the Electron Exchange Animation (EEA) having at least four of six characteristics unique to this animation and no more than one unique characteristic of the PEA, and thus they were referred to as Pro EEA as they favored the Electron Exchange Animation. The second group of four students (2 females and 2 males) revised their drawn and oral explanations to fit nearly exclusively with the Physical Exchange Animation (PEA) having at least four of five characteristics unique to this animation and no more than one characteristic of the EEA. As a result, they were referred to as the Pro PEA group. These two groups are the focus of this manuscript so that we can better understand how these students came to agree so exclusively with one of the two animations. This was analyzed based on how these students responded to the metacognitive monitoring exercises in which each student was asked: (i) Review your list and compare it to the list you made for the animation. What things do you have in common? Circle or mark the items that you have in common. Tell me what you circled and why you believe it matches? (ii) Using a different marker color, mark the features of the animation that are dissimilar to yours. Describe what you marked and why these are dissimilar to each other? (iii) Which animation is a better representation of the atomic level event. Describe your reasoning.

Following the study, the session was transcribed and an open coding process was used to study how the students recognized variation and agreement between their understanding of the reaction and what was shown in the animation (Merriam, 2009). A constant comparative method of data analysis was used to study the descriptions students gave for why they found their understanding similar to and different from each animation and categories were developed to describe the nature of the chemistry that they noticed (Merriam, 2009; Glaser & Strauss, 1967). For example, if students discussed how the EEA showed electrons being exchanged or cloud movement this indicated that they noticed the electron exchange mechanism. If they discussed how water molecules were involved in the movement of ions this was labeled ''Role of Water'' (Tables 1—4). The categories are provided so that the reader may assess the accuracy of the author's conclusion and the internal validity of the study.

Results and discussion

Electron exchange animation

Similarities and differences observed by Pro EEA students

As a reminder, students were asked: How did the list of characteristics they depicted in their hand drawn atomic level representations compare and contrast to the list of characteristics they observed in each animation? The students who became Pro EEA consisted of three students: S8, S16 and S17 (Table 1). They were very detailed in describing how their representations and understanding differed from the animation. All three students described characteristics that fit under the codes ''electron exchange mechanism'' and the ''role of water'' (Table 1). Both S8 and S17 noticed that the copper ion released in the EEA did not have to occur at the same location where the silver ion attached to the copper surface. All three students expressed that they were initially unaware of the importance of water molecules in hydrating the ions and the ''competition'' they had for the positive ion. Some students gained clarification from the animation. For example, S8 noticed that silver crystals formed on the wire, while S16 learned that nitrates do not have anything to do with the reaction. Only one of the students, S17, recognized that his drawing was more detailed than the animation in explicitly showing how copper formed a copper(II) ion and lost two electrons in the process. When asked how their features were similar to the animations, the three students noticed that there was a ''physical mechanism'' that matched with what they saw in the EEA (Table 1). All three, recognized that they had a commonality in that silver metal formed on the surface of the copper wire. These students also recognized chemical species that were in common (''Species involved''), for example, S16 and S17 commented that they had ions in their depictions and so did the animation. While S8 recognized that water molecules were common to both. Only one of the members of this group recognized that electrons were exchanged (''Electron exchange mechanism'') and this matched with the EEA.

Similarities and differences observed by Pro PEA students

The students who were Pro PEA exhibited a range of detail in their description of how their understanding differed from the EEA (Table 2). Only two of the students, S10 and S11 discussed the electron exchange mechanism, which was the hallmark of the animation. S10 observed that there was a gain in cloud from copper to silver. He had no idea that valence electrons were involved. S11 admitted that she did not address the gaining and losing of electrons in her pictures. She did not include electron clouds and she was unaware that ''ions'' could lose electrons at a different part

Table 1 Response of Pro-EEA students to the electron exchange animation.

	What differences did students notice between their 'key features' and those they identified in the EEA?
S8	1. Electron exchange mechanism a) . . .but I didn't know that it(silver) would gain electrons in the cloud there were electrons. I didn't know that the silver ion would gain one electron worth of cloud. . . silver would gain electrons. b) . . .that the copper would even lose cloud c) I didn't know like for every two electrons the copper would lose, silver would gain two electrons and like the different times that it would happen. 2. Role of water a) I didn't know that it was hydrated silver ions and I didn't know that the water molecule would hydrate the copper. b) That there would be a competition for a positive ion 3. Species involved a) I didn't know that it was silver crystal. 4. Physical mechanism b) That hydrated ion would come from a different part of the lattice.
S16	1. Electron exchange mechanism a) The electrons as well, I just kind of completely ignored that. . . . Showing that silver gains an electron and copper loses them or however many it does gain or lose. I didn't really have anything going on about that at all. 2. Role of water a) I don't have water at all, in my drawings, whereas here it is kind of showing that water is a key player in this reaction. Whereas me, I was just completely ignoring it thinking it had nothing to do with it. b) The tug of war, I kind of like that and I think that is dissimilar. It's sort of similar, sort of not, but I do show there is something going on, but I wasn't illustrating the water. I'm going to say that was completely different. 3. Physical mechanism a) I illustrated some movement but I guess not all movement. 4. Species involved a) I do have nitrate in there but I just don't have something explaining that this has nothing to do with the current reaction, it's just kind of hanging around.
S17	1. Electron exchange mechanism a) I emphasized that copper metal becomes an ion, a copper two ion and it loses two electrons. In the animation I definitely see that really specified. They do show it in a ratio, but they don't relate it back to how that's dependent on exchange of electrons. And through my description I really emphasize that point. 2. Role of water a) The ions were in hydration shells and they were oriented depending on the type of ion. 3. Physical mechanism a) the loss of copper from the wire doesn't necessarily have to occur at the same location as where the silver is forming onto the copper wire. b) Here I just kind of demonstrated more so that the silver just kind of forms on any exposed surface area of the wire. I did not necessarily think to draw it where the ions could form on the silver metal that's already there.
	What similarities did students notice between their 'key features' and those they identified in the EEA?
S8	1. Physical mechanism a) Copper leaves, got that! b) I knew that silver formed c) I knew that it(silver) would switch 2. Species involved a) I knew there was a water molecule.
S16	1. Physical mechanism a) I sort of had this one, this forming of the silver solid. b) I illustrated some movement 2. Species involved a) I had ions and they had ions. b) I do have nitrate in there c) Silver solid and crystal structure, I had that.
S17	1. Electron exchange mechanism a) Exchange of electrons 2. Physical mechanism a) Silver metal formed on the surface of the copper wire 3. Species involved a) Free floating ions in solution

Table 2 Response of Pro PEA students to the electron exchange animation.

	What differences did students notice between their 'key features' and those they identified in the EEA?
S9	1. Physical mechanism a) There are two silver ions that go into copper ions right here. I didn't draw that here. b) I thought that the silver ions just touched the copper and it just left with the copper. But I didn't know that it made the silver atoms as well. 2. Species involved a) I didn't know that the nitrate doesn't do anything. b) silver ions added to make silver atoms. 3. Role of water a) But I think in the animation it showed more of the copper attaching itself to the water, it wasn't the chemicals. . . .it left with four water molecules.
S10	1. Electron exchange mechanism a) . . .gains cloud from copper, gives it to silver. Okay so I had no idea that there were valence electrons included whatsoever so I didn't mention that anywhere here. b) The valence electrons swapped between the two ions
S11	1. Electron exchange mechanism a) losing and gaining electrons because I did not even put anything related to gaining and losing electrons. b) Copper ions lose electrons at different part of lattice; silver ions gain electrons. c) I didn't put anything about electron clouds 2. Role of water a) Hydrated H_2O molecules move away from silver ion. That's actually, that's kind of like my first drawing. That kind of looks like my first drawing, but I didn't draw any H_2O molecules, just silver and nitrogen. So I guess I will underline that because it's not, I didn't draw the H_2O molecules. b) Hydrating water and copper competing for silver. I kind of just assumed that silver and copper would immediately react without the water interfering. c) copper ions leave as hydrated ions at different part of lattice. 3. Species involved a) I guess the silver builds part so that was just silver that built on there? I did not know that. Well right, um, I mean I didn't know that it was silver, but I knew that something had built up on it 4. Physical Mechanism a) copper ions leave lattice.
S12	1. Role of water a) water was present and it attached to some of the copper atoms 2. Species involved a) Okay, there is a nitrate ion that comes out of nowhere. b) but I could tell from the video that water was present
	What similarities did students notice between their 'key features' and those they identified in the EEA?
S9	None
S10	1. Physical mechanism a) Vibrations in the beginning and molecules were moving more closely together. That there were movement and vibrations in the beginning and they were kind of floating around and that they are moving closely together and I mentioned that the copper and silver nitrate were moving closely together, which they were.
S11	1. Physical mechanism a) Silver ions join lattice b) Silver ions can build on silver crystals.
S12	1. Electron Exchange a) Yeah, I put that it gained electrons. 2. Physical mechanism a) that the $AgNO_3$ attached to the copper lattice. $AgNO_3$ attaches to the copper ion. I used the same word, attaching to bits of the copper atoms b) I put that the silver ions kind of took off some of the copper and attached to themselves. c) Copper atom loses electrons (depicted in EEA) so that kind of correlates with (copper wire) got thinner.

of the lattice. Notice that she incorrectly noted that the ion lost the electrons when it was a neutral atom. Three of the four students noticed the role of water in the process. However, understanding the importance of the ion's charge necessary for attracting polar water molecules was less understood. For example, S11 observed that ''Hydrated water molecules move away from the silver ion.'' But this is actually incorrect as the water molecules move away only

Table 3 Response of Pro-EEA students to the physical exchange animation.

	What differences did students notice between their 'key features' and those they identified in the PEA?
S8	1. Physical exchange mechanism a) Nitrate ion taking a copper molecule. 2. Role of water a) but I didn't look at the water, I should have 3. Species involved a) nitrate was one compound that would break off as a whole and not separate individually. I didn't know that was the nitrate ion because I broke the nitrogen up with the oxygen. So having that as a whole should have been a no duh, but it wasn't. b) copper (II) nitrate, I did not know that that would form.
S16	1. Role of water a) Water molecules are there, but I didn't have them in my drawing so that wasn't similar. ... I wasn't sure what they were doing in the reaction.
S17	1. Species involved a) ...the video doesn't make a distinction between the ion and the solid metal, but I did do that when I was drawing my images. 2. Macroscopic connection a) the video showed a before and after of the copper wire on eye level. I didn't include one of those.
	What similarities did students notice between their 'key features' and those they identified in the PEA?
S8	1. Physical exchange mechanism a) took a copper molecule because I knew that the copper would break off. I also knew that the silver would form with the copper row. 2. Species involved. a) I knew that silver stayed! See I got that part right! 3. Macroscopic connection a) I circled the copper wire placed and then went into the solution, I mean that was easy it was placed in the solution.
S16	1. Physical exchange mechanism a) Nitrate ions pulling the copper ions, that's actually what I did draw! So that's what I thought was going on, I thought that nitrate ions just taking them away and then silver was just doing its thing. b) And the silver molecules bonding on their own, that's kind of like what I was going for not in the best way but that's what I was trying to go about with. 2. Species involved a) Illustration of copper nitrate, I suppose I had it to an extent. b) And the silver molecules bonding on their own, that's kind of like what I was going for not in the best way but that's what I was trying to go about with. 3. Macroscopic connection a) Representation of the experiment on a macro scale, I somewhat have that with the kind of blob that I drew there, which is in the picture, to kind of this is copper and nitrate and then inside the solution you've got a bluish color.
S17	1. Stoichiometric connection a) It did show a clear ratio of the silver and copper II nitrate, interaction as products you are going to get two silver metal formed and you are going to get one mole of copper nitrate formed and I kind of describe that in my image here after 8-minute image. 2. Simplified the reaction a) The video was simplified it took away a lot of the other, it didn't really represent all the ions that could have been present and I did that too.

after the ion has become neutral in charge. S9 observed that it was the copper that attached itself to the water, but she did not describe the charge. S12 stated that water was present and attached to some of the copper atoms, but he was unclear of the importance of charge in this process. Most of the students identified that the animation clarified chemical species involved in the reaction. S9 and S11 noticed, although with some uncertainty from S11, that silver built up on the wire. S9 and S12 noticed the presence of the nitrate ions.

Students who were Pro PEA ranged in how they compared with the EEA, but in general they had noticeably little in common with the animation (Table 2). Only one student, S9, recognized that she had nothing in common to it. S10 noted that the only shared characteristic was the depiction of movement, described as vibrating and floating, and the distance between chemical species was similarly depicted. S11, similar to the Pro EEA students, observed that she showed ions joining the lattice and that silver ions could build on silver atoms. Only one student, S12, claimed that

Table 4 Response of Pro-PEA students to the physical exchange animation.

	What differences did students notice between their 'key features' and those they identified in the PEA?
S9	1. Physical exchange mechanism a) nitrate takes the copper but it bounces off too.
S10	1. Physical exchange mechanism a) The silver ion was kind of replacing it, the copper ion, and just thought it was the chemical reaction for a color change I didn't think it was turning into silver. b) Silver nitrate, comes and releases silver ions. 2. Role of water a) The water had no effect. I can't match that anywhere in mine. 3. Species involved a) I circled the copper ion or atom are all together. I didn't mention that anywhere here. I just mentioned that they were mingling around.
S11	1. Physical exchange mechanism a) copper was partially replaced by that's what differed too. I mean like instead of silver just covering the copper and it still being copper underneath, I think that this is saying that that is not the case that it actually became silver and there were actually copper ions now in the solution making it copper nitrate. The silver and the copper switched. 2. Species involved a) It became copper nitrate, I had that it was unchanged.
S12	1. Physical exchange mechanism a) When the nitrate broke off and left the silver, it took some copper and made a copper nitrate ion that flew away b) . . .And I didn't really specify that silver was attaching to copper and forming and staying behind. c) Speed of atom collide with each other − I didn't specify how fast the reaction was happening from the video (means animation) I could tell that the atoms collided fairly fast
	What similarities did students notice between their 'key features' and those they identified in the PEA?
S9	1. Physical exchange mechanism a) when the nitrate holds on to the copper wire. I wrote here that it attaches itself to the copper molecule. the silver holds onto the copper and nitrate takes copper but bounces off with the liquid. 2. Role of water a) So there is water in it, it's passing through.
S10	1. Species involved a) when they were traveling the ions were all like closely together so that was similar but they weren't really mingling. Just the mingling of the molecules, like the water molecules, like they were just floating around.
S11	None
S12	1. Physical exchange mechanism a) I put that the AgNO3 with the nitrate was taking atoms off of the copper wire, making it thinner. I thought that it was taking off atoms completely forming copper nitrate. I didn't put copper nitrate, but I put the copper atoms were being lost. b) I put that the silver nitrate reacted and in Picture 2 I had the reaction goes on or the reaction is present. 2. Macroscopic connection a) The copper wire looks darker than when it started and it also looks thinner. I put right here (on his list) that the copper wire looks thinner than when it first started.

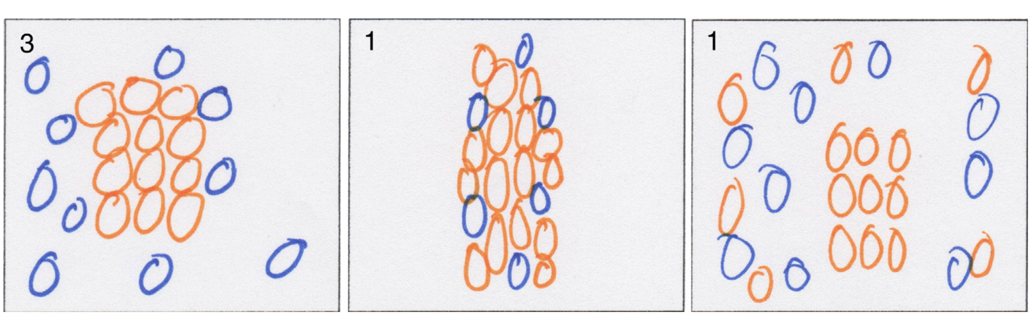

Figure 2 The first picture shows silver nitrate as blue circles moving toward the copper wire. The middle picture has the silver nitrate attached to the copper atoms. The third picture shows the silver nitrate attaching to copper atoms and drawing them away from the copper.

he depicted gaining of electrons, but he did not actually incorporate this into his drawings made prior to seeing the animations (Fig. 2). However, in his written list of features he stated, ''the $AgNO_3$ atoms are drawn closer to the copper atoms because they want to fill their octets.''

When asked to clarify this, S12 stated:

> *I'm not sure how to explain this...So the $AgNO_3$ is kind of like, it's attaching to the copper, because the copper is in there, the AgNO3 is all around it, and it slowly takes off atoms from the copper because, it's kind of like how water and salt act. Water combines and takes atoms away because for that octet or something like that. And so the $AgNO_3$ kind of attaches to the copper for a little bit and as the reaction went on, it took bits of it off, leaving the copper much thinner.*

When S12 was asked to clarify what he meant by octet he stated: ''So that's when atoms move to fill their outer orbits with eight electrons, because they might not have that so they attach to other atoms so they can share and take some of their electrons.'' In S12's drawing there was no visible indication that electrons were transferred, but upon seeing the EEA, S12 felt that his understanding was in agreement with this aspect of the animation.

Physical exchange animation

Similarities and differences observed by Pro EEA students

The students who became Pro EEA initially noticed very little difference between their key features and those represented in the PEA (Table 3). Two of the students, S16 and S17, did not recognize the physical exchange mechanism as differing from their work. However, S8 noticed that the animation emphasized the nitrate ion taking a copper molecule while she had actually broken the nitrate ion into separate atoms in her initial depiction. S8 was attentive to the formation of copper(II) nitrate depicted in the animation, while she did not show this. S16 found that the animation showed water molecules while he did not and he stated that he was not sure what they were doing in the reaction. Water did not play an active role in the animation. S17 noticed a limitation of the PEA was that it did not distinguish atoms from ions as he had done in his drawings, but he also noticed that a strength was that the animation provided a macroscopic connection that he found very useful.

When the students were asked to describe similarities between the PEA features and what they drew and listed as important features, the Pro-EEA students tended to notice similarities with the physical exchange mechanism or the stoichiometric attributes of the visualization. For example, S16 stated ''Nitrate ions pulling the copper ions, that is actually what I did draw!'' S8 shared that she knew that the copper would break off and that silver would form on the copper, while S17 recognized the stoichiometric similarities noting that they both showed a clear ratio of the silver and copper(II) nitrate leading to the production of ''two silver metals'' and ''one mole of copper nitrate.'' In addition, both S8 and S16 noticed that the animation connected explicitly to the macroscopic evidence and they made an effort to do this too. S17 recognized that this video simplified the reaction by showing fewer reacting species and he acknowledged that he made an effort to simplify the reaction too. It is important to note that in spite of their initial agreement with the less accurate animation, S8, S16, and S17 were able to recognize that the EEA was a better representation and they made revisions that reflected their new understanding.

Similarities and differences observed by Pro PEA students

The students who eventually became Pro-PEA varied in their recognition of ways that their understanding was similar to the PEA (Table 4). Only two students, S10 and S11, expressed that they had relatively little in common with the animations. S11 felt that she did not have anything in common with this animation while S10 found only the proximity of the species and the way that they floated and mingled matched with her initial conception. Students, S9 and S12, expressed that aspects of the physical exchange mechanism matched with their initial depictions. S9 stated, ''...when the nitrate holds onto the copper wire, I wrote that it attaches itself to the copper molecule...the silver holds onto the copper and nitrate takes copper, but bounces off with the liquid. Similarly, S12 stated, ''I put that the $AgNO_3$ with the nitrate was taking atoms off of the copper wire, making it thinner. I thought it was taking off atoms completely forming copper nitrate.''

The students who became Pro PEA revealed that a big difference between their depiction and the PEA was in the physical exchange mechanism (Table 4). All four students, described the mechanism in which the nitrates exchanged a silver for a copper atom, leaving the silver on the surface of the copper, while the ''copper nitrate'' went into solution or ''flew away.'' In addition to noticing this mechanism, one student, S10, noticed that water had no effect and he admitted that he did not address water at all in his pictures. S11 recognized that copper nitrate was formed and this was different than she had thought. S12 noticed that the speed of the collision was something that was well represented in the animation, but he had not anticipated its importance in his depictions.

Pro PEA students reasons for choosing the PEA as the best animation

When the students were asked which animation they preferred and why. The students who chose the PEA expressed that they preferred it, because it made sense to them and it was easier to understand than the EEA. S11 found it easier to draw than the EEA and he also preferred the connection to the macroscopic level.

> *S11: It(PEA) actually explains that, I mean that you can deduct from it that the solution changes because it shows the, again I think it was like what I was saying about the other animation was up too close. ...but with this one it was just easier for me to accept that the copper being taken away is what happens... the silver nitrate leaves the silver on the wire and takes a copper to make it the copper nitrate.*

S12 shared that the animation was more relatable because it combined seeing the experiment at the atomic level with the everyday level. He felt that having both perspectives were helpful.

S12: The graphics were much better than the graphics in the other one. And then on the atomic level I think it was better too, because at the beginning I saw that the atoms collided super-fast. From that I could understand if something is coming fast then also kind of breaks off and just the physical aspect is there. It's present. I can see it breaking off into, taking chunks of it off and leaving, whereas in the other one I saw slowly, then it dropped and then it took one. The speed, just the mannerisms of it all, just fit together better.

Similarly, S10 shared that even though the PEA was vaguer and there were no descriptions or a narrator saying what happened, he still preferred it because it was ''easier to see'' and ''what really made it clear was when it showed the silver nitrate attaching on and replacing the copper.''

S10: Like to be honest, I don't even know. But if I were to be put in a room to see and they asked me like which one could you understand better, it would definitely be this one (refers to the PEA). Just because it's more, not like hands on, I don't know how to explain it. You actually see what's happening compared to just observation. I don't know, just like, it's more clear to me, like what's exactly happening. And even if it's not right, I can definitely explain what's happening.

S9 could not understand why in the EEA the water molecules would attract to the copper ion and leave the silver behind.

...it was kind of weird, because in the first animation(PEA) the water molecule just passed through. But it seemed like it was the spectator or whatever that is. But in this visual(PEA) it's the nitrate ion and it's the water molecules (in the EEA) that are doing the work. Yeah. Which one do I think is right? Probably the nitrate (PEA) because I'm not sure about the water because the water didn't react when it was in the copper, in the experiment.

In this case S9 had difficulty understanding the connection to the experimental evidence, in which it was demonstrated that when a copper wire was placed in distilled water, there was no reaction between the wire and the water. The student made the application that in all cases water would not react.

Pro EEA students reasons for choosing the EEA as the best animation

The students who were Pro EEA did not necessarily think that the PEA was incorrect. Some thought that the PEA was a more simplistic version of the EEA. These students also found some benefits to viewing the PEA. For example, S8, after viewing the PEA recognized flaws in her depictions.

So what I drew can be confusing and it doesn't really show. They (the PEA) show the exact molecules. You see one nitrogen and you see three nitrogen and you see how it's paired. You have silver nitrate. ...And then mine is not drawn to scale. You don't see exactly what happened between them so you can't see that what paired with what and what broke off and what stayed together.

S8 also felt overwhelmed by the EEA and admitted, ''it was hard to kind of keep track of what was going on. I had to go back and forth.'' However, when S8 was asked which animation she preferred. She said. ''I think both videos that you showed supported it (the experimental evidence). I think they were just on different levels...the first video (PEA) answered what happened and then this video (EEA) answered how it happened.'' When S8 made her revisions it was clear that she favored the EEA, but during the interview she expressed that it was hard to draw to a conclusion and when she was pressed to give a reason for which animation was more accurate she struggled.

S8: *I mean I understand the H2O would hydrate the copper atom. But then this one showing that it's not the H2O that it's causing it to break apart. That it's the nitrate.*

R: *Yeah, so what do you think about it. Which one's right?*

S8: *Well, aahhh, umm.*

R: *What does your experimental evidence tell you?*

S8: *This is hard! I still think that this one's right (pointing to the pictures that she drew from the EEA)*

R: *Why?*

S8: *Because I think that, I don't know, maybe I do, maybe I don't. Maybe it's because it's this one (PEA) is more convincing than the other one. Like this(PEA) is more correct in the fact that everything is the same size, it's simpler, or it doesn't go in depth like why it happens. The second one(EEA) is more accurate like as far as the atomic mass and the atomic radius on the periodic table and like, so I would think that, I don't know, it's talking about more like how it happened, and why it happens. And I think it's more convincing so if the first ones right, it's not very convincing why it would be right. The second one the way that it shows it, it's more convincing.*

S16 initially indicated that in order for him to determine which animation was the better representation, he would need to know what was really happening. He recognized that both animations covered the main points that silver formed on top of the copper wire and parts of the copper broke apart. However, S16 noticed that the mechanisms were different, the PEA showed that nitrate was involved in drawing the copper ion into solution, while the EEA showed that it was the water molecules. S16 was convinced by the detail of the electrons being exchanged that convinced S16 that the EEA was the better animation.

S16: 'Cause it was talking about the electrons and it's better at showing that too, that there are some electrons gained and lost whereas this one with the key, I don't know if you can see that with the camera or not, but with the key it just has, this could be an ion or it could be an atom. It doesn't really show you what's going on.... So, it just really failed on that point.

However, at the end of the interview, when S16 was asked once again what convinced him that the EEA was the better animation. He stated that he started to think about the water more and the PEA showed the nitrate reacting with the copper and taking it away, but he observed that that was not what happened in the experiment. He then described that since the solution was found to be conductive this evidence implied that ions were present in solution and that the copper nitrate that was shown in the first animation could not be correct as it would not conduct if it stayed together. In addition, he admitted that he initially thought that the nitrate was involved as it was shown in the PEA, but he knew that in redox reactions, electrons were lost and gained and this knowledge also assisted him in recognizing that the EEA was the better animation. Thus it seems that S16 tapped into his prior knowledge of redox reactions and he also drew upon the experimental evidence to reach his conclusion.

S17 was also highly influenced by his prior knowledge of redox reactions and his ability to comprehend how the hydration shells were formed by water molecules that were oriented depending on the type of ion they surrounded. In addition, S17 was able to connect how the evidence supported the animation and discussed the formation of the silver on the surface and how the color change of the solution could be due to the copper ions in that were drawn into the solution. While S17 admitted that he believed the PEA was incorrect, he still found it useful for explaining the balanced molecular equation.

Limitations

The animations were different from each other not only in their mechanism but in the details. If the animations were constructed to be identical apart from the mechanism, then we could learn how students make sense of the mechanism. We are currently working to design animations that are similar apart from the mechanism to examine how this affects students' ability to discern which is the better mechanism. In addition, since this was a very small group of students generalizability is limited.

Conclusions

This study highlights how students compare and contrast their understanding to two animations to decide which animation is most scientifically accurate. It reveals that students pick up on the mechanistic differences between the animations, but they struggle with understanding why it happens. Regardless of their background knowledge of chemistry, students prefer animations that are simplistic in their appearance and obvious in what they convey while also having an explicit connection to the macroscopic level. However, it is important to note that the participants desired more explicit models because the whole point of the exercise was for them to determine which model best fit with the experimental evidence. This may imply that students want assurance that they are ''getting the right answer'' as they worry about their grades or it may imply that the task is inherently difficult and students may need more scaffolds to manage the task.

In general, most of the students were certain that the EEA explained how the reaction was happening better than the PEA, because it had more details and a narration that explained what was happening. However, the less cluttered and more distant view of the chemical species in the PEA with an obvious connection to the macroscopic reaction was appealing to most of the students because it made it easier to understand. From this metacognitive monitoring exercise, we learned, as mentioned, that students were able to detect the mechanistic difference between the animations, but sometimes they ignored the mechanistic difference and decided that the PEA was a simplified version of the EEA. Some even equated this with how they learn to balance an equation because the equation has a different mechanism, ions appear to switch partners, while the submicroscopic level does not portray this as a switch. Students struggled with whether to accept a model that clearly showed a physical collision resulting in nitrate ions that were freed to attract to copper, a mechanism that fit with a single replacement equation model or to accept that an animation that was more conceptually sophisticated requiring them to apply their understanding of ion-dipole intermolecular forces and electron transfer from neutral atoms to ions must be taking place. Through the interview it was apparent that students found it difficult to understand how and why intermolecular forces between water molecules and ions happened. It was also difficult for them to account for why and how electron transfer happened between silver and copper. In general, students who successfully chose the EEA were better able to make sense of the core concepts of electron transfer, the role of water and the physical connection to the experimental results. Students who were inclined to choose the PEA were less able to interpret the role of water and the electron exchange. They followed the logic of the physical exchange of the cation by the nitrates portrayed in the PEA because it lacked water and resembled the equation.

Implications

Having students critique animations and decide which animation was the better representation of a redox reaction resulted in many students choosing the least accurate animation. This may be upsetting to some instructors who fear that viewing an animation that is wrong could reinforce student misconceptions. From this study, most students conveyed uncertainty with their selection regardless of whether they chose the EEA or the PEA, thus it is unlikely that the exercise reinforced a misconception. Instead, the practice of critiquing the animations seemed to raise students' awareness of the limitations of their own pictures for conveying what they thought about conceptually. One student, S8, commented,

> ''So what I drew can be confusing and it doesn't really show the exact molecules... mine is not neat at all and then it is not drawn to scale. You don't see exactly what happened between them so you can't see what paired with what. ...I don't think if somebody looked at my picture that they would be able to identify what was necessarily going on.''

S17 commented, ''When I was doing that I was also considering, okay, what are the mistakes I am making. You know, what are the things I'm leaving out that might, if somebody else were to look at my notes, would they be confused?'' This exercise in self-reflection may be the most important benefit of this exercise and over time may lead to deeper understanding.

No matter how scientifically accurate the designer hopes to make the animation, they will contain flaws. It is the nature of all animations. They are simplifications of complex events. In the past, students tended to trust all animations over their own representations not recognizing that animations could be wrongly portraying aspects of a phenomenon. When students are suddenly presented with a situation in which the animations could be wrong and they contrast with each other, the students are empowered to decide for themselves, which is the better animation. In addition, they have a reason to pay closer attention to the animation details, and they must weigh whether they trust the animation or not through connection to experimental evidence or from prior experiences in learning. Even if they choose the wrong animation, they have learned an important facet of science that of justifying atomic level theories through careful analysis and connection to experimental evidence.

Conflict of interest

The authors declare that they have no conflicts of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.eq.2017.02.003.

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