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Is the oxygen atom static or dynamic? The effect of generating animations on students' mental models of atomic structure

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> Have me watch videos, I forget;
> Ask me to do online interactives, I remember;
> Let me produce and create, I learn.
> *Jackie Gerstein (Educational Technologist)*

Visualizing the chemical structure and dynamics of particles has been challenging for many students; therefore, various visualizations and tools have been used in chemistry education. For science educators, it has been important to understand how students visualize and represent particular phenomena -- i.e., their mental models-- to design more effective learning environments. This study aimed to investigate and compare students' *static* and dynamic representations of mental models for a fundamental concept of chemistry, atomic structure. Static representations of mental models were expressed as drawings and explanations given on paper, with *dynamic* ones being generated by using animation-developing software. This mixed-method study was implemented in three parts. A total of 523 10th (N=277) and 11th (246) grade high school students participated in a workshop where they first learned how to use one of three animation-developing software programs (K-Sketch, Chemsense or Pencil; N= 162, 204, 157, respectively), and then prepared an animation of an oxygen atom using that program. Before and after creating the animation, students were asked to draw the structure of the atom and to storyboard the oxygen atom for three seconds. After students generated their animations they were asked to explain their animations in 2-3 minute interviews (N=324). The static and dynamic representations of mental models were compared statistically by the Wilcoxon Signed Rank Test within each group, and they were compared by the Kruskall Wallis Test between the groups. The results of the analysis showed that in all the groups, a significant difference ($p=0.000$) between the initial and final static representations of mental models suggested that students modified their mental models towards a more refined and accurate representation of the atomic structure. Regardless of the software program used, students included significantly more dynamic features ($p=0.000$) in their static representations of mental models after generating animations than they did initially. No significant difference ($p>0.05$) between any of the features was conveyed in static representations of mental models of students who worked with different software programs. In addition, student-generated animations revealed some misconceptions, such as movement of the parts of the atom or the atom itself besides electrons, which were not detected on paper.

Key Words: Animation-developing software program, mental model, animation, oxygen atom.

Introduction

Learning chemistry involves understanding and relating chemical phenomena at macroscopic, symbolic, and particulate levels (Johnstone, 1993, Taber, 2013a). High school and college general chemistry classes usually emphasize the macroscopic and the symbolic levels over the particulate level. This could be due to the difficulty of visualizing the structure, behavior, and the processes taking place at the particulate level and relating them to the macroscopic level (Nakleh, 1992; Smith et. al. 2006). For this reason, instructors have been using models and modeling activities to represent the particulate level and help students visualize the particles, as well as make the concepts more explicit. The models used to enrich the instruction include drawings, pictures, physical models or computer-based models such as animations and simulations (Williamson, 2008). Another way of using models is to let students create their own, which will possibly reveal their mental models. These representations show how students visualize certain phenomena and could be generated in different forms such as *static* or *dynamic*. These representations of mental models are generated by using different media such as paper-and-pencil (Akaygun & Jones, 2013a) or playdough-and-sticks (Uyulgan *et. al.*, 2010) for static; and animation-developing and modeling software programs (Schank & Kozma, 2002, Xie & Pallant, 2011) for dynamic ones. For science educators it is important to know whether the type of medium affects the models generated by students, therefore it is crucial for the instructors to select the best medium according to the needs of the students.

The purpose of this study was to compare how students visualize and model an oxygen atom in terms of their *static* representations of mental models, as expressed in drawings and explanations given on paper, and *dynamic* representations of mental models, which were animations created using one of three programs: K-Sketch, ChemSense or Pencil.

Understanding chemistry

Considering the three levels of chemical phenomena, chemistry knowledge can be classified as *experiences*, which refers to empirical knowledge about chemical systems; *models*, which includes the descriptive, explanatory and theoretical models used to describe chemical systems; and *visualizations*, which constitute the static and dynamic representations of symbols, formulas, physical models, graphics, animations and simulations (Talanquer, 2011). For a good understanding of chemistry, students should be able to translate knowledge from one form to the other.

In chemistry classes, many instructors focus mostly on two of the three levels: the macroscopic (experiences) and symbolic levels (visualizations); however, it cannot be assumed that students understand the relationship between observable and particulate levels as chemists do (Nakhleh, 1992, Smith et al., 2006, Talanquer, 2012). It is particularly important for students to understand the submicroscopic level, because the nature of chemical processes can only be explained by the motion and behavior of particles. Researchers suggest that instruction emphasizing the level of particles would help students learn chemistry conceptually (Davidowitz & Chittleborough, 2009; Driver, 1985; Gabel, 1993, 1999). For this reason, instructors prefer to use supporting tools such as models and modeling activities to help students understand the structure and behavior of particles (Williamson, 2008).

Understanding the nature of particles - in other words, the atomic and molecular structures and dynamics -- has also been challenging for students, who may develop alternative conceptions/frameworks, naïve theories or intuitive beliefs. Previously, it has been reported that students may have specific misconceptions related to the structure, shape, size, weight, and animistic perceptions of atoms (Cokelez & Dumon, 2005; Griffith & Preston, 1992; Papageorgiou, et.al, 2016; Papaphotis & Tsaparlis, 2008). Thus, they may have difficulty separating models from reality, describing atoms as *balls, plums,* or *cells* (Harrison & Treagust, 1996), or as *solar systems* (Nakiboglu, 2003, 2008; Papaphotis & Tsaparlis, 2008), regardless of the curriculum and language they study (Nakiboglu & Taber, 2013). In research investigating students' understanding of atoms, the responses provided were usually written (via paper and pencil) or verbal (via interviews). Therefore the explanations obtained mostly included static representations. In order to have a more coherent understanding of students' understanding of the atom, a medium which allows users to represent dynamics should be used. It appears to be a triggering question for the researcher if the environment has any impact on determining any new misconceptions on atom involving motion, by using animation-developing software program, which cannot be determined otherwise. Therefore, a software program that develops animation -- in other words, a modeling tool which helps students generate dynamic models in the form of animations -- was selected as the medium to be used in this study.

Models and modeling

Scientific phenomena seem especially complicated to novice learners. Hence, most of the time, scientists and science educators have preferred to use different forms of representation, namely *models*, to communicate their ideas and explanations regarding scientific phenomena. Kinnear and Martin (1992) define the model and its functions as follows:

> 'A *model* is 'a simplified picture or representation of a complex object or process. Models can help us understand how an object is constructed or how a process occurs. A good model also helps us make predictions about how an object will behave. A model, however, is not the real thing and accepted models can change as new information becomes available (p.10)'.

Modeling is described as an attempt to construct a model of a system (Bodner, et. al., 2005). The role of models and modeling in various modes has been found to be an essential part of science education (Mathews, 2007; Williamson, 2008, Levy, 2013). In chemical education especially, due to the difficulty of visualizing the structure and behavior of particles -- concepts which are vital in conceptualizing the chemical phenomena -- models are used to simulate the particulate level: the structure and dynamics of atom and molecules. Smith et al. (2006) argue that modeling is especially important for the introduction of atomic-molecular theory in middle school because students need to comprehend entities such as atoms, molecules, and forces, which cannot be directly observed.

Various kinds of models have been used in science education. Early on, concrete models were preferred. Gabel and Sherwood (1980) showed that the manipulation of molecular models helped high school chemistry students improve their chemistry achievement. Later, analogical models were used to represent the particulate level. In a study by Gabel, Briner, and Haines (1992) chemistry teachers used a “hands-on” approach involving placing magnets on a pizza pan to represent evaporation of water molecules. The authors suggested that teachers should model the physical phenomena so that students can relate the macroscopic events to the particulate level.

Another type of model that students have been exposed to is the visual models presented in textbooks. Justi and Gilbert (2000) investigated the atomic models represented in the textbooks, and suggested that only a limited number of models of atom exist. The authors identified six models relevant to the science curriculum, namely the *Ancient Greek model, Dalton’s model, Thomson’s ‘embedded mass’ model, Rutherford’s ‘nuclear’ model, Bohr’s ‘orbit’ model,* and the *quantum mechanics model*. Researchers have found similar patterns between these representations and the ones given by students (Harrison & Treagust, 1996, 2000; Nakiboglu, 2003, 2008; Nakiboglu & Taber, 2013).

Models and modeling in science classes can be implemented in various ways. Windschitl, Thompson, & Braaten (2008) argue that the use of models is often limited to illustrative and communicative purposes as instructional tools when teachers use them in the classroom or laboratory. However, learners can also generate models while learning science. Justi and Gilbert (2005), in their analysis of models and modeling from the perspectives of students, teachers and textbooks, suggest that introducing modeling activities helps students improve their ability to build their own models. In addition, involving students in modeling processes can help them improve their subject matter expertise, conceptual understanding, construction and evaluation of scientific knowledge, and ability to build models (Lehrer & Schauble, 2006; Schwarz & White, 2005; Schwarz et al., 2009). Schwarz et al. (2009) argue that it is crucial to involve learners in the construction of models rather than primarily working with models provided by teachers or scientific authorities because through constructing, using, and evaluating their own models learners proceed through a learning progression as they improve their meta-knowledge.

Recent advances in educational technology accelerated the use of computer-based modeling practices in science (Leenaars, van Joolingen & Bollen, 2013; Wu, 2010) and chemistry lessons (Chang, Quintaan & Krajcik, 2010; Chiu & Wu, 2009; Levy, 2013). In order to elicit student difficulties in connecting the different representational modes for understanding chemical concepts researchers have recently developed a variety of computer-based modeling tools such as MARS, Model-It, STELLA, ThinkerTools (Metcalf, Krajcik, & Soloway, 2000; Raghavan, Sartoris, & Glaser, 1998; Stratford, 1997; White, 1993), Slowmation (Hoban, et.al., 2010, 2011), ChemViz (Beckwith & Nelson, 1998), eChem (Wu, Krajcik & Soloway, 2001), Vischem (Tasker & Dalton, 2006), ChemSense (Schank & Kozma, 2002), ChemDiscovery (Agapova, Jones & Ushakov, 2002), ChemLogo (Stieff & Wilensky, 2002), K-Sketch (Davis, et.al. 2008), PhET (Wieman, et al., 2008), Molecular Workbench (Xie & Pallant, 2011), and Chemation (Chang, Quintaan, & Krajcik, 2010).

The introduction of computer-based modelling tools in science education has enabled researchers to investigate its effects on students’ learning outcomes because these tools provide environments where students can freely display their thinking. In other words, student-generated representations (drawings, models or animations) can be assessed to evaluate their understandings. One commonly used computer-based modelling tool, Model-It (Metcalf, Krajcik, & Soloway, 2000; Stratford, Krajcik, & Soloway, 1998), enables students to build models involving dynamic phenomena, such as light, water, and the carbon cycle. Model-It provides scaffolds to learners through unique features such as icons representing objects, measurable or calculable variables, and relationship arrows. It has been reported that the computer-based modelling software programs such as MARS, Model-It, STELLA, and ThinkerTools have been used to elicit learners’ understandings; when appropriately used, they all can improve conceptual understanding, inquiry skills, and systems thinking (Richmond, 2001; Valanides & Angeli, 2008).

Another important type of computer-based modelling tools used for modelling is animation-developing software programs. One example, Slowmation, is a tool used for stop-motion animation where users can incorporate object animation and digital storytelling. Slowmation has been used to investigate how students create a new way of learning about science concepts such as atoms, electricity, and insects. Several studies (Hoban, McDonald, & Ferry, 2009; Hoban, Loughran, & Nielsen, 2011; Hoban & Nielsen, 2012, 2013) asked preservice elementary teachers to design and create a narrated animation to represent their knowledge of science using Slowmation. In their study, Hoban, et.al. (2009) allowed participants to incorporate different forms of media such as text, diagrams, graphs, gestures, music, layout, images (still and moving), and 2D and 3D models, as well as voice, to facilitate learning. The authors argue that by using Slowmation, learners not only engage with content when creating an animation, but develop an understanding of the scientific content because they reflect on it in different ways.

ChemSense is a computer-based modelling and animation-developing tool specifically designed for teaching and learning chemistry. It includes different representations depicting atoms, bonds, or tools such as the Periodic Table, graphs, and text to create drawings and animations. Trunfio et.al. (2003) argue that ChemSense provides students with a more diverse set of tools to increase the ways they demonstrate their chemical understandings. ChemSense has been used to investigate students' understandings in various topics of chemistry, and researchers have found that using ChemSense helped learners construct a deeper understanding of chemistry (Chan, 2002; Schank & Kozma, 2002, Trunfio, et.al. 2003).

Another tool of this kind, Chemation, allows users to create 2-D molecular models and flipbook-style animations of chemical phenomena. In one study, Chang, Quintana & Krajcik, (2007) examined the impact of using Chemation on 7th grade students' conceptual understanding as they designed, interpreted and evaluated animations. The results of this study revealed that engaging students in the process of designing and evaluating their own animations has a significantly positive effect on student development of conceptual understanding.

While some computer-based modelling tools have been specifically designed to generate specific science models and animations, some others, e.g. K-Sketch (Davis, Colwell, & Landay, 2008), have been used to generate general-purpose animations regardless of a specific subject area. Davis et.al (2008) have developed K-Sketch, a research-based, informal, 2D animation sketching system, to help novices create a wide range of animations quickly. The authors compared K-Sketch to a more formal animation tool (PowerPoint) and found that participants worked three times faster, needed half the learning time, and had a significantly lower cognitive load with K-Sketch.

Besides various modelling activities, in general, student-generated representations, including drawings, are often used to elicit students' understandings. Research on generating drawings suggests that they help students make connections with their prior knowledge (Akaygun & Jones, 2013; Chi, 2009; Rich & Blake, 1994; Zhang & Linn, 2011). In a study conducted by Rich and Black (1994), students were asked to draw their views before and after reading a text. The authors reported that asking students to draw their ideas before reading texts elicited students' prior knowledge and promoted discussion, whereas asking them to draw after reading helped them integrate their ideas with the prior knowledge. Chi (2009) suggests that drawing is an active process in which students recognize the conflicts among their ideas and examine and repair them. In their study, Zhang & Linn (2011) asked students to create drawings to model a chemical reaction as they interacted with a dynamic visualization. Authors argued that, throughout the process of drawing, students were engaged purposeful in modeling practices and hence advanced their understanding of scientific concepts.

Therefore, in this study, students were introduced to a significant modeling activity through a computer-based modeling tool, in which they built their own dynamic models representing their visualization and understanding of the structure of atom in the form of animations. In other words, through this modeling activity, they were able to communicate their understanding of atoms by generating dynamic representations. Before and after generating animations students were asked to draw representations which would help them interact with their prior knowledge.

Mental models

Mental models are the small-scale representations created by people as a result of their perception, imagination, experience and interaction with reality (Craik, 1943, Johnson-Laird, 1983). Mental models have usually been represented through words or pictures, each of which may have different affordances. Because they are representations of some kind, they are referred to *representations of mental models*. Yet, these environments may not be sufficient to accurately depict chemical phenomena which include dynamic entities. Therefore, animation-developing software programs would provide an alternative environment to display mental models. Hence, in this study, students presented their mental models of the oxygen atom in two different environments: on paper (static) and through animation (dynamic). Then, the static and dynamic representations of mental models were compared and contrasted to determine whether the environment had any effect on representations due to their affordances.

Although mental models are internalized abstract constructs and cannot be directly measured, various methods have been used to elicit representations of mental models. For identifying complex mental representations, more open-ended methods such as interviews, think-aloud protocols, and open-ended questionnaires are suggested to be used to access more information than simple multiple choice questions (Tversky et al., 2006). Thus, in this study, open-ended questions, individually generated animations, and semi-structured short interviews were used. On the other hand, mental models are not rigid, but open to change; they can be revised as individuals cognitively work on the task (Gilbert, 2004). Jones et al. (2011) argue that mental models are constructed in working memory, which is the system for selecting and manipulating information for reasoning and learning. Therefore, this study aimed to investigate whether any change in the representations of mental models would occur as a result of creating a model in the form of an animation of an oxygen atom.

Purpose of the study

Chemical phenomena involve both *static* features such as structure of atoms and molecules, and *dynamic* ones such as motion and interaction within and between the particles. In general, ’students' drawings and explanations of their mental models may have limited structural features and are less likely include dynamic features. Therefore, animation-developing software programs could be used as modeling environments where students create visual versions of their mental models of the concepts involving motion and interaction.

The purpose of this study was to elicit and compare students’ mental models of oxygen atoms generated on paper with those generated through one of three software programs: K-Sketch, ChemSense, and Pencil. Three different programs were chosen in order to test the consistency of the results. All three studies were conducted in the form of a 3-hour workshop. In the beginning of the workshop students first took the pre-tests, and then were taught to create animations using the designated animation-developing software program. In the second part of the workshop, students were asked to use the software program to model an oxygen atom. In addition, the study also aimed to investigate the effect of this modeling activity on their mental models of the atom. In other words, it aimed to investigate the extent to which modeling helped them transfer their visualization and understanding from a dynamic computer-based environment to a static paper-pencil environment.

Oxygen was selected for the study because it is a small atom that can easily be modeled and the students were familiar with it. In the beginning of the study, the atomic and mass numbers of oxygen were given, and the students were notified that even though in nature oxygen is found as a diatomic molecule, in this activity they would be working on a single atom of oxygen.

The study is novel in terms of using two different types of modeling environments to elicit and compare students’ representations of mental models; as well as investigating the effects of creating dynamic models of atomic structure by using three different animation-developing software programs on students’ static representations of mental models. Research findings show that it is helpful for students to build their own models not only to improve their meta-knowledge (Schwarz et al., 2009), but also conceptual understanding (Lehrer & Schauble, 2006; Schwarze & White, 200); thus, the environments (paper-pencil and animation-developing software programs) provided in the study allowed students to create their own models from scratch instead of using an already existing model. Lastly, the study is timely because it included a computer-based modeling environment which helped students include dynamic features such as the spinning of electrons, and it helps instructors and researchers to identify motion-related misconceptions that are hard to identify in static models.

Methodology

Design

The study used a *mixed method* design where the students’ static and dynamic representations of mental models were investigated by making use of both quantitative and qualitative research methods (Creswell, 2012). Specifically, *exploratory sequential design,* in which qualitative data collection is followed by quantitative analysis and then interpreted by connecting these two phases, was adopted (Creswell & Clark, 2010). For the quantitative design, one-group quasi-experimental pretest-posttest design was adopted for the study. For the qualitative part, the theoretical framework of phenomenography, which aims to discover different ways in which people experience, conceptualize, realize and understand various aspects of phenomena in the world around them (Bowden et al., 1992) was used. In this respect, student drawings of the atom, student-generated animations, and the interviews were analyzed. The study was implemented three times following the same procedure, using three different software programs: K-Sketch, ChemSense, and Pencil.

Participants

The participants in all three studies were selected from 10th and 11th grade students in seven different Turkish public high schools with similar characteristics. Before starting the study, an approval from the Institutional Review Board (IRB) was obtained. Then the selected schools were contacted and permission from the administrators and teachers was obtained. Before the workshops, students were informed about the aim of the study, and they were told that there would be no harm to students in the study; in fact they would benefit by learning how to use a software program that they could later use for their own tasks. The teachers acted *in loco parentis* and decided that as long as the children volunteered, parental permission was not needed (Taber, 2014). The number of students who voluntarily participated in each study is shown in Table 1.

Table 1. The number of 10th and 11th grade students who participated in each study.

Grade Level	K-Sketch (N)	ChemSense (N)	Pencil (N)	Total (N)
10th Grade	87	110	80	**277**
11th Grade	75	94	77	**246**
Total (N)	**162**	**204**	**157**	**523**

When the participants' responses given in the pretest were compared using the Wilcoxon Sign Rank Test with respect to their schools and grade levels, no significant difference ($p>0.05$) was found in either case. Therefore the groups could be considered equivalent. For this reason the 10th and 11th grade students who worked with a specific software program (K-Sketch, ChemSense or Pencil) were grouped together, resulting in three groups to be studied.

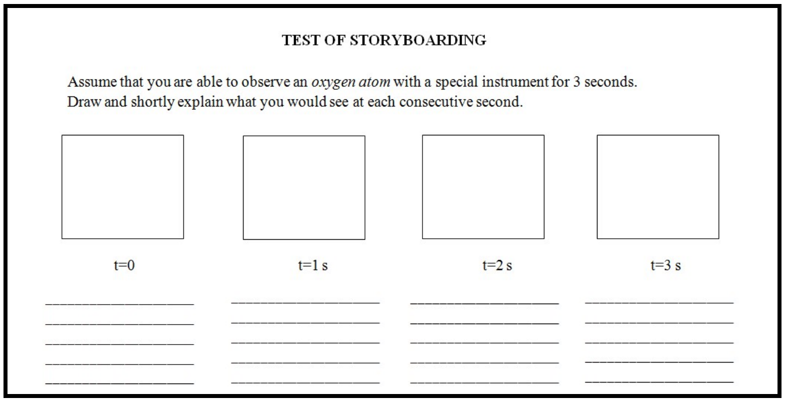
Instrumentation and data collection

In the study, students attended an *Animation Developing Workshop* given at either their school's or the University's computer laboratories. In each workshop, students came from one school and one grade level in intact classes. Before and after the implementation of the workshop, students took a *Demographics Questionnaire*, *Draw an Atom Test-Pre (DAT-Pre)*, and *Storyboard an Atom Test-Pre (SBAT-Pre).* All instruments were prepared by the researcher and validated by two chemistry professors. The implementation of paper tests took about 20-25 minutes. After they generated their animations of the oxygen atom, the students were interviewed using a short semi-structured interview protocol. In the three studies, a total of 324 (62%) of the students were interviewed. Finally, the students retook the *Draw an Atom Test-Post (DAT-Post)* and *Storyboard an Atom Test-Post (SBAT-Post)* at the end of the implementation.

Demographics Questionnaire (DQ). In the *Demographics Questionnaire*, besides the demographic information such as age, gender, grade point average, career choice, etc., students were also asked about their knowledge, skills, and experiences with computers and computer visualizations used in chemistry.

Draw an Atom Test (DAT-Pre & DAT-Post). In the Turkish National Science Curriculum, the subject *atom* is first introduced in the 7th grade science and technology course. Then it is elaborated in the 9th grade, and finally *Modern Atomic Theory* is covered in the first semester of grade 10. By the time the study was conducted, all the students had completed this unit. In the *Draw an Atom Test*, students were specifically asked to draw and explain the structure of an oxygen atom. The analysis of this question aimed to elicit students' expressed static representations of mental models (given on paper) of the atom.

Storyboard an Atom Test (SBAT-Pre & SBAT-Post). In the *Storyboard an Atom Test*, students were asked to storyboard an oxygen atom for three seconds, consecutively, in the boxes provided, and explain their drawing in the space provided. The reason for giving this test was to guide students to think about any changes that might take place if they were able to observe an atom for three seconds. In other words, it aimed to cue students for the motions involved in an oxygen atom, which they may not have considered in the *Draw an Atom Test*. However, students were not told that those three seconds represented an incredibly long time when compared to the timescales of atomic/molecular motion. Figure 1 shows the question asked in the *Storyboard an Atom Test.*



TEST OF STORYBOARDING

Assume that you are able to observe an *oxygen atom* with a special instrument for 3 seconds.
Draw and shortly explain what you would see at each consecutive second.

t=0
t=1 s
t=2 s
t=3 s

Figure 1. The question asked in the *Storyboard an Atom Test*.

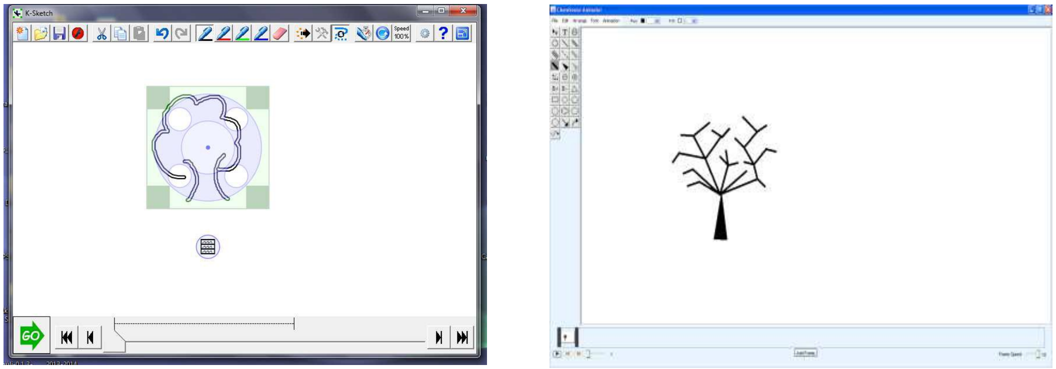
Interview protocol. After students generated their animations, they were asked to explain whether they showed everything they wanted to show in the animations, how they represented the motion, their experience with using the software, difficulties they had, and aspects they liked and disliked about the specific software program they used.

Animation-developing software programs

Kinetic Sketch Pad (K-Sketch). K-Sketch (URL-1) is a software program designed to generate basic two-dimensional animations using a drawing and animation tool which lets users move, orient, translate, rotate, spin, reflect and change the size of the figures they draw (Davis, 2008). Although K-Sketch (Figure 2 (a)) was not specifically designed for teaching and learning chemistry, it is a tool that could be used in chemistry classes.

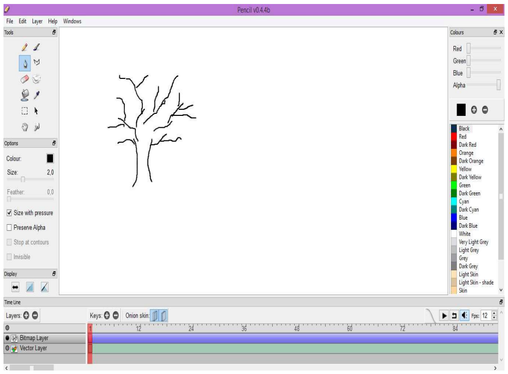
ChemSense. ChemSense (URL-2) is a software program specifically designed to generate drawings and animations for chemistry concepts through a stop-motion technique. ChemSense (Figure 2 (b)) includes various tools such as Periodic Table, bond angle and bond type needed for chemistry animations.

Pencil. Pencil (URL-3) is another software program used to create 2-dimensional sketches and animations using a stop-motion technique. Pencil (Figure 2 (c)) has a rich color palette and offers the feature of importing pictures from the outside and animating them, an option the other programs lack.



(a)

(b)

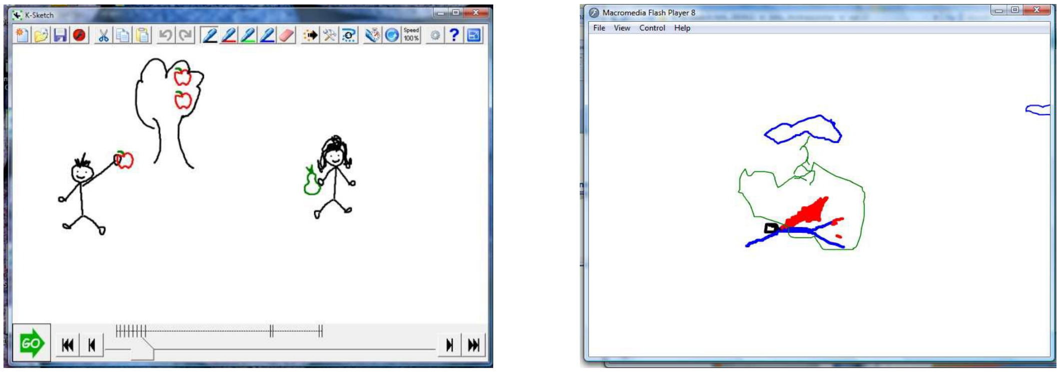


(c)

Figure 2. Drawing canvas and a sample tree drawn in (a) K-Sketch, (b) ChemSense, (c) Pencil.

Implementation of an animation-developing workshop

The implementation consisted of an *Animation Developing Workshop*. In the first part, students learned how to use the software programs (K-Sketch, ChemSense or Pencil) for 45-60 minutes; in the second part, they individually generated an animation of an oxygen atom in about 20-30 minutes. While the students were learning how to use the software, they were guided to generate two animations unrelated to chemistry, such as kids picking apples, asteroids moving in space, or a superhero. Figure 3 shows sample screen shots from the animations generated by the students during this stage. During the implementation, two assistant pre-service teachers stood by to help the students with technical difficulties such as not being able to spin an object or not being able to move two objects at the same time. However, the assistants did not help them with the content related to the structure of the oxygen atom.



(a) (b)

Figure 3. Sample screen shots from the animations generated by the students while learning how to use K-Sketch: (a) animation of kids picking apples; (b) animation of a superhero.

In each workshop, the students' chemistry teachers also participated in the workshop, but they only observed their students and did not work with the software themselves. Surprisingly, in one of the K-Sketch workshops, one computer teacher also participated and learned how to use the program. After the workshop, she said she found the program very useful and decided to teach the program to the rest of the students at her school.

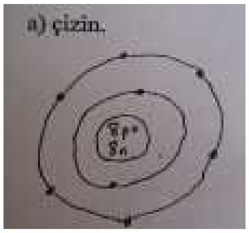
Data analysis

For the data analysis, the static and dynamic representations of students' mental models of oxygen atoms were first coded through open coding. Then the emergent codes were collapsed into categories such as type of atomic model, structure of the atom, and representation of motion. Table 2 shows the coding rubric used in the analysis of both static and dynamic representations . For the 'type of atomic model' codes that emerged, the last three (Dalton, Bohr and Modern integrated) atomic models were consistent with the categories suggested by Justi and Gilbert (2000).

Table 2. Coding rubric used in the analysis of static and dynamic representations of mental models.

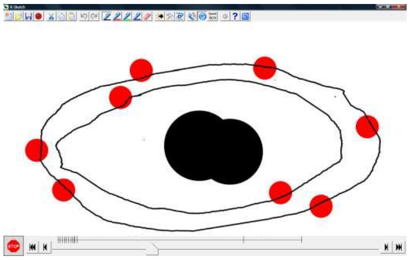
Type of atomic model 0: No representation 1: Lewis /Symbolic 2: Dalton's model 3: Bohr's model 4: Modern integrated model	**Representation of Electron** 0: No representation 1: By using dots 2: By using numbers 3: By using e-/ -	**Representation of nucleus** 0: No representation 1: Empty Circular 2: Including only protons 3: Including p & n	**Representation of orbital** 0: No representation 1: Circular 2: Eliptical 3: Modern/integrated
Representation of motion: 0: No representation 1: Motion represented **Giving Explanations:** 0: No explanation 1: About structure 2: About motion 3: About process	**Type of motion:** 0: No motion 1: Zooming 2: Motion of atom 3: Bonding 4: Motion of parts 5: Motion of electrons 6: Motion of e- & parts	**Motion of electrons:** 0: No motion 1: Bonding/ e- transfer 2: Rotation 3: Free motion 4: Spin & rotate	**Using color:** 0: No use of color 1: Coloring nucleus 2: Coloring p & n 3: Coloring electrons 4: Coloring orbitals 5: Color coding

Figure 4 shows a sample coding for a drawing or static mental model; Figure 5 shows sample coding for an animation or dynamic mental model.



Type of atomic model: 2 (Bohr's model)
Representation of Electron: 1 (By using dots)
Representation of nucleus: 2 (Including p ve n)
Representation of orbital: 1 (Circular - continuous)
Representation of motion: 0 (No representation)
Use of key or label: 1 (Key or label is used for p & n)
Misconception: 0 (No misconception observed)

Figure 4. A sample coding for a paper-pencil drawing or static mental model.



Type of atomic model: 2 (Bohr's model)
Representation of Electron: 1 (By using dots)
Representation of nucleus: 1 (Full circular)
Representation of orbital: 1 (Circular - continuous)
Representation of motion: 1 (Motion represented)
Type of motion: 1 (Rotation of electrons around the nucleus)
Use of key or label: 0 (No key or label is used)
Misconception: 0 (No misconception observed)

Figure 5. A sample coding for a K-Sketch animation or dynamic mental model.

The inter-rater reliability was achieved by reaching 95% agreement after another science education researcher coded 15 % of the static and dynamic representations of the oxygen atom. Finally, the categories which lie on a continuum of giving either more accurate or more detailed information were statistically compared by the Wilcoxon Sign Rank Test analysis.

Results and Discussion

I. Participant characteristics

The findings related to the demographics of the participants showed that 51% of the students were 16 years old and 49% were 17. In terms of the gender, 52% were female. The majority (51%) had begun to use a personal computer while they were in the 1st -5th grade, and 31% said they had learned how to use computers in pre-school. Even though some (23%) were familiar with visualization programs, the majority (60%) knew only Microsoft Office programs. Surprisingly, the majority (67%) reported that they had never seen a computer visualization of chemistry.

II. Comparison of mental models

The initial static, dynamic and final static representations of mental models were compared based on two main aspects that emerged from data: *structural* and *dynamic* features. Structural features included type of atomic model, representation of electron, representation of nucleus, and representation of orbitals; dynamic features included representation of motion, type of motion, and motion of electrons.

Structural features. The structural features that emerged in the representations of mental models were type of atomic model, representation of electron, representation of nucleus, and representation of orbitals.

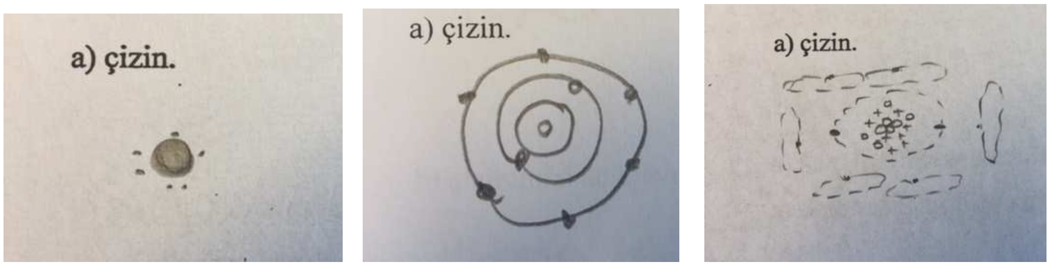
Representation of type of atomic model. When the static and dynamic representations of mental models were compared according to the categories that emerged in the study, a significant difference was found between different initial and final representations of mental models in certain categories for all the students who used an animation-developing software program. *Type of atomic model* was one of the categories found to be significantly different in initial static, dynamic, and final static representations of mental models. Specifically, the atomic model representations depicted in initial static representations of mental models were significantly different (p=0.000) from the ones displayed by animations. Similarly, the final static representations of mental models were significantly different (p=0.000) than both the dynamic and the initial static ones in terms of the type of atomic model displayed, as seen in Table 3. Figure 6 shows sample representations for the type of atomic models displayed in static representations of mental models; Figure 7 shows similar representations depicted dynamically by animations (See ESI 1 for the electronic version of the animation).

Table 3. Percentages of students who u used K-Sketch, ChemSense and Pencil, with respect to different types of atomic model representations, in DAT-Pre, animations and DAT-Post.

Software Program	Type of Atomic Model	(DAT-Pre vs. animation)*	(animation vs. DAT-Post)*	(DAT-Pre vs. DAT-Post)*
		DAT-Pre	**Animation**	**DAT-Post**
K-Sketch	Symbolic Model	19%	2%	10%
	Bohr's Model	75%	74%	74%
	Modern Integrated Model	6%	24%	16%
ChemSense	Symbolic Model	22%	5%	7%
	Bohr's Model	74%	81%	82%
	Modern Integrated Model	4%	14%	11%
Pencil	Symbolic Model	18%	2%	7%
	Bohr's Model	79%	82%	83%
	Modern Integrated Model	3%	16%	10%

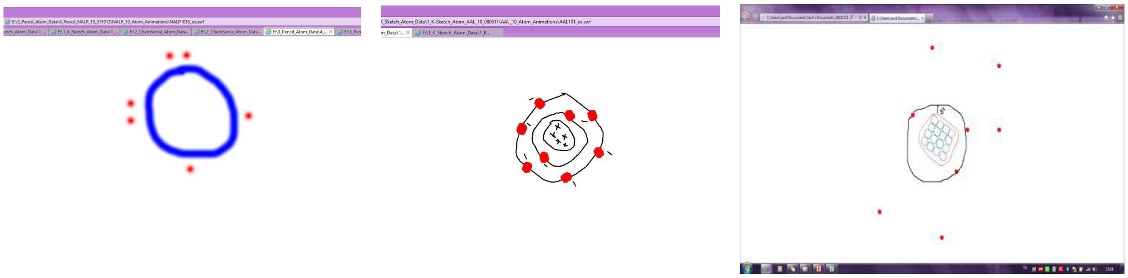
* The difference was found to be significantly different (p=0.000).

Regardless of the software program used by the students, it was observed that there was a significant (p=0.000) decrease in symbolic representations and a significant (p=0.000) increase in the modern integrated representations from initial static to dynamic and final static representations of mental models.



(a) (b) (c)

Figure 6. Sample representations for the type of atomic models -- (a) Symbolic Model, (b) Bohr's Model, (c) Modern Integrated Model -- depicted in static representations of mental models.



(a) (b) (c)

Figure 7. Sample representations for the type of atomic models -- (a) Symbolic Model, (b) Bohr's Model, (c) Modern Integrated Model --depicted in dynamic representations of mental models.

When the types of atomic models represented in the *Storyboard an Atom Test* were analyzed, a different type of atomic model, Dalton's model, which was not observed in DAT, was observed. Figure 8 shows an example of a student's atomic model representation from SBAT-Pre and SBAT-Post. This student depicted Dalton's Model in their SBAT-Pre and Bohr's Model representation in their SBAT-Post. However, when the atomic models conveyed in the SBAT-Pre and SBAT-Post were compared before and after generating animations with a particular software program, the percentage of students who used Dalton's Model significantly decreased and the percentage who used Bohr's Model increased significantly. This might have happened due to the fact that after generating animations students started to show more structural details. Table 4 shows the percentage of students who conveyed a specific type of atomic model representation in the *Storyboard an Atom Test* and the animations.

Table 4. Percentage of students who used each software program with respect to representations of type of atomic models in SBAT-Pre, animations and SBAT-Post.

Software Program	**Type of Atomic Model**	**(SBAT-Pre vs. animation)***	**(animation vs. SBAT-Post)***	**(SBAT-Pre vs. SBAT-Post)***
		SBAT-Pre	**Animation**	**SBAT-Post**
K-Sketch	Symbolic Model	9%	0%	2%
	Dalton's Model	19%	2%	9%
	Bohr's Model	58%	74%	74%
	Modern Integrated Model	15%	24%	15%
ChemSense	Symbolic Model	5%	2%	2%
	Dalton's Model	20%	3%	14%
	Bohr's Model	65%	81%	73%
	Modern Integrated Model	10%	14%	11%
enc	Symbolic Model	3%	2%	2%

	Dalton's Model	21%	0%	13%
	Bohr's Model	68%	82%	77%
	Modern Integrated Model	8%	16%	8%

* The difference was found to be significant (p=0.000).

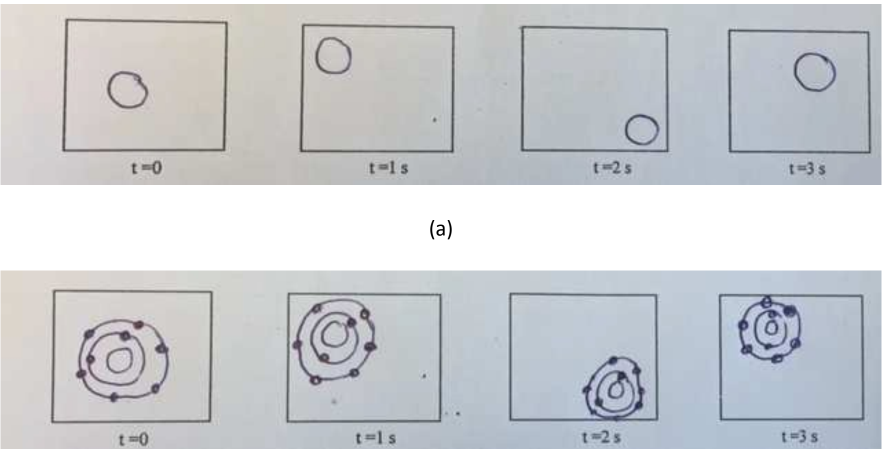
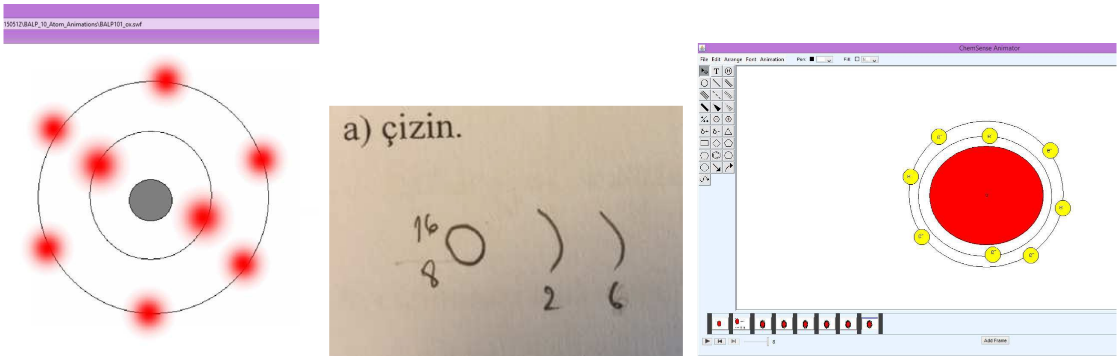


Figure 8. One student's atomic model representation conveyed in (a) SBAT-Pre and (b) SBAT-Post.

Representations of mental models were categorized as a whole, and also compared with respect to other depicted structural features such as electrons, nucleus, and orbitals.

Representation of electrons. When the students' static and dynamic representations of mental models for atomic structure were analyzed, it was seen that students had represented electrons by using three different representations -- dots, numbers and symbols -- from less information to more information. Figure 9 shows how electrons were represented in certain static (b) and dynamic (a and c) representations of mental models.



(a) (b) (c)

Figure 9. Representation of electrons in static and dynamic representations of mental models, as (a) dots, (b) numbers, (c) symbols.

When mental models were compared in terms of the representation of electrons before and after generating an animation, no significant difference ($p>0.05$) was found between initial and final static representations in all three groups. However, significant differences were found between static (both initial and final) and dynamic representations of mental models, as seen in Table 5. When the students were asked to draw or animate, they used different structural representations and focused on different features. Namely, they provided details (symbol or charge) in drawings, whereas in animation (K-Sketch & Pencil), they focused on the particulate feature, which is why they showed electrons as dots. The ChemSense software program provides a symbol for electrons, which is why they tended to use the symbol when they created animations. If the symbol was not provided in the software program, they used particles (dots or circles) to represent electrons.

Table 5. Percentage of students who used K-Sketch, ChemSense and Pencil, with respect to representations of electrons in SBAT-Pre, animations and SBAT-Post.

Software Program	**Representation of Electrons**	**(DAT-Pre vs. animation)***	**(animation vs. DAT-Post)***	**(DAT-Pre vs. DAT-Post)+**
		DAT-Pre	**Animation**	**DAT-Post**
K-Sketch	Dots	80%	92%	84%
	Numbers	5%	--	2%
	Symbols (e-)	15%	8%	14%
ChemSense	Dots	71%	63%	72%
	Numbers	8%	2%	4%
	Symbols (e-)	21%	35%	24%
Pencil	Dots	75%	94%	81%
	Numbers	8%	--	5%
	Symbols (e-)	17%	6%	14%

* All the differences were found to be significant ($p=0.000$).

Representation of the nucleus. The analysis of static and dynamic representations of mental models revealed that the nucleus was either represented as an empty circle (e.g. Figure 9 (a)), a circle containing only protons (e.g. Figure 7 (b)), or a circle containing both protons and neutrons (e.g. Figure 6 (c)). When these representations were compared, no significant difference ($p>0.05$) was found among them. This might suggest that developing an animation did not cause any significant change in students' representation of a structural feature, because they might have focused on the dynamic features instead of structural ones.

Table 6. Percentage of students who used K-Sketch, ChemSense and Pencil, with respect to representations of orbitals in SBAT-Pre, animations and SBAT-Post.

Software Program	Representation of Orbitals	(DAT-Pre vs. animation)*+*	(animation vs. DAT-Post)++*	(DAT-Pre vs. DAT-Post)*++
		DAT-Pre	Animation	DAT-Post
K-Sketch	Circular	98%	84%	86%
	Elliptical	1%	15%	13%
	Modern Integrated	1%	1%	1%
ChemSense	Circular	93%	85%	88%
	Elliptical	3%	15%	11%
	Modern Integrated	4%	---	1%
Pencil	Circular	96%	84%	89%
	Elliptical	1%	10%	10%
	Modern Integrated	3%	6%	1%

* The difference was found to be significant (p=0.000).
+ The difference was not found to be significant (p>0.05).
The three symbols represent the significance of each analysis conducted for K-Sketch, ChemSense, and Pencil, respectively.

Representation of orbitals. When the static and dynamic representations of mental models were compared with respect to the representation of orbitals, significant differences were found, as seen in Table 6. The initial static and dynamic representations created with K-Sketch and Pencil were significantly different ($p<0.05$). Circular orbits were the all-time favorite in all the representations of mental models. Moreover, in all the groups, students were more likely to depict orbitals on paper with circles, whereas they tended to use elliptical orbitals in their animations. This might have resulted in part from the elliptical drawing tools available in ChemSense and Pencil.

Dynamic features. The second aspect referred to in the comparison of representations of mental models was the dynamic features, which emerged as representation of motion, type of motion, and motion of electrons.

Representation of motion. When the students' static and dynamic representations of mental models were compared in terms of motion conveyed in SBAT and animations, it was observed that the percentage of students who represented motion in SBAT increased significantly ($p<0.05$) in all three programs, as seen in Table 8. These results may suggest that generating animations improved students' representation of motion when they were provided with an appropriate environment. In addition, when they were provided with empty boxes to represent change in time time frame, as in case of SBAT, they focused more on dynamics, even though they were still significantly less likely to show motion on paper compared to animations.

Table 7. Percentage of students who used K-Sketch, ChemSense and Pencil, with respect to representations of motion in SBAT-Pre, animations and SBAT-Post.

Software Program	Representation of Motion	(SBAT-Pre vs. animation)*	(animation vs. SBAT-Post)*	(SBAT-Pre vs. SBAT-Post)*
		SBAT-Pre	Animation	SBAT-Post
K-Sketch	No motion	27%	4%	13%
	Motion	73%	96%	87%
Chem Sense	No motion	33%	1%	21%
	Motion	67%	99%	79%
Pencil	No motion	29%	0%	18%
	Motion	71%	100%	82%

* All the differences were found to be significant (p=0.000).

Representation of type of motion. The analysis of static and dynamic representations of mental models conveyed by storyboarding and animation showed that students tended to depict different types of motion when they were provided a proper medium to represent motion, as seen in Table 9. Motion of electrons was represented by the highest number of students, but other types of motions, such as the motion of the atom, motion of other parts of the atom, bonding, or zooming, were also observed. In the representation of zooming, students first zoomed from a distance to inside the atom and then represented the structure. When the initial and final static representations of mental models were compared, it was observed that, regardless of the software program used, students showed motion of electrons significantly ($p<0.05$) more in the SBAT-Post. Interestingly, in all groups, the percentage of students who showed the motion of parts of the atom (nucleus, orbitals, or protons/neutrons) or the motion of atom itself (besides the motion of electrons) was higher in the animations than on paper. This might suggest that generating animations helped students convey different types of motions that they thought were happening more than storyboarding did. Figure 10 shows screenshots of the animations depicting different types of motion(See ESI 2 for the electronic version of the animations).

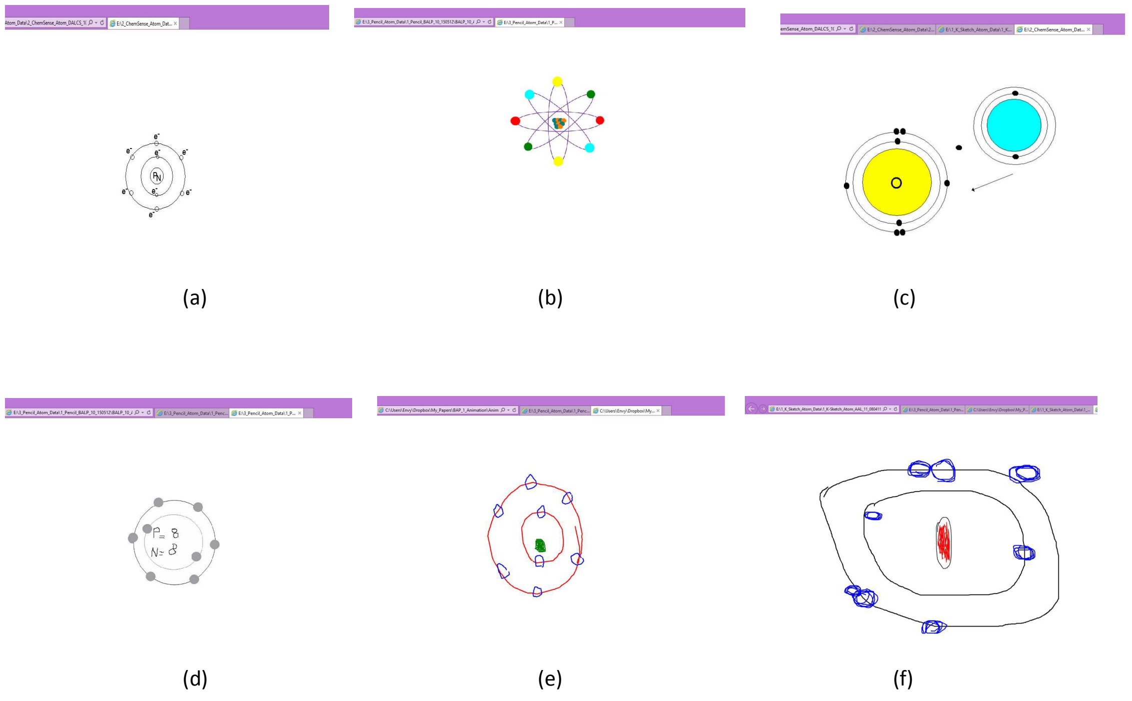


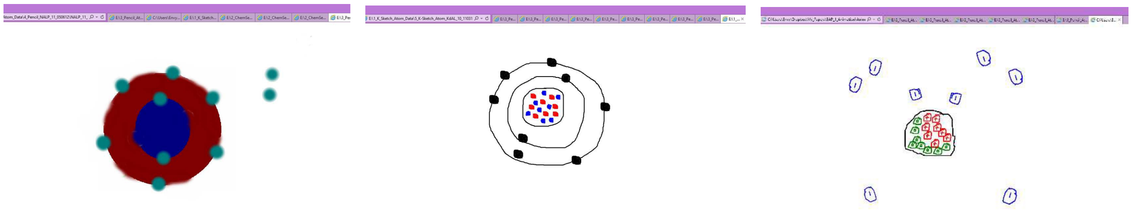
Figure 10. Screenshots of the animations showing different types of motion: (a) zooming, (b) motion of atom, (c) bonding, (d) motion of parts, (e) motion of electrons, and (f) motion of electrons and parts.

Table 8. Percentage of students who used K-Sketch, ChemSense and Pencil, with respect to representations of type of motion in SBAT-Pre, animations and SBAT-Post.

Software Program	Type of Motion	(SBAT-Pre vs. animation)*	(animation vs. SBAT-Post)+*+	(SBAT-Pre vs. SBAT-Post)*
		SBAT-Pre	Animation	SBAT-Post
K-Sketch	No motion	21%	4%	9%
	Zooming	4%	--	3%
	Motion of atom	16%	17%	12%
	Bonding	6%	1%	2%
	Motion of parts	4%	17%	2%
	Motion of electrons	42%	47%	64%
	Motion of electrons & parts	7%	14%	8%
ChemSense	No motion	20%	1%	10%
	Zooming	9%	7%	8%
	Motion of atom	14%	13%	17%
	Bonding	11%	12%	10%
	Motion of parts	2%	4%	3%
	Motion of electrons	36%	35%	45%
	Motion of electrons & parts	8%	28%	8%
Pencil	No motion	15%	4%	13%
	Zooming	12%	--	9%
	Motion of atom	22%	19%	15%
	Bonding	6%	5%	2%
	Motion of parts	2%	2%	1%
	Motion of electrons	39%	48%	52%
	Motion of electrons & parts	6%	23%	9%

* The difference was found to be significant (p=0.000).
+ The difference was not found to be significant (p>0.05).
The three symbols represent the significance of each analysis conducted for K-Sketch, ChemSense, and Pencil, respectively.

Representation of motion of electrons. Even though students represented motion in both their static and dynamic representations of mental models, they conveyed different types of motions of electrons, such as rotation, spinning, free motion and transfer. When the static and dynamic representations of mental models were compared with respect to the motion of electrons displayed, significant differences were observed, as seen in Table 9. Specifically, for the students who used K-Sketch and Pencil, there was a significant difference between the initial and final static representations of mental models. The percentage of students who showed the rotation of electrons increased from initial to final representations, whereas for the students who used ChemSense to generate animations, no significant difference was observed. This might have happened due to the greater emphasis ChemSense places on structural features over motion compared to other two software programs. Figure 11 shows screenshots of the animations depicting different types of motion of electrons.



(a) (b) (c)

Figure 11. Screenshots of animations showing different types of motion of electrons; (a) electron transfer, (b) rotation, (c) spin and rotate

Table 9. Percentage of students who used K-Sketch, ChemSense and Pencil, with respect to representations of type of motion of electrons in SBAT-Pre, animations and SBAT-Post.

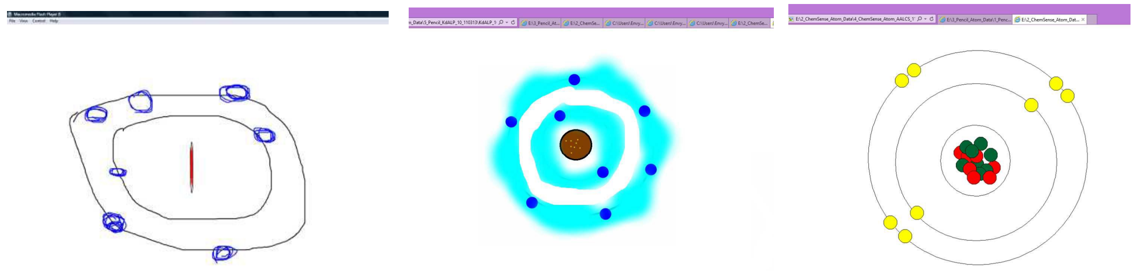
Software Program	Motion of electrons	(SBAT-Pre vs. animation)*	(animation vs. SBAT-Post)+*+	(SBAT-Pre vs. SBAT-Post)*+*
		SBAT-Pre	Animation	SBAT-Post
K-Sketch	No motion	44%	33%	27%
	Bonding / e-Transfer	6%	1%	1%
	Rotation	40%	42%	59%
	Free motion	4%	4%	3%
	Spin & rotate	6%	20%	10%
ChemSense	No motion	47%	28%	39%
	Bonding / e-Transfer	11%	13%	9%
	Rotation	36%	55%	48%
	Free motion	3%	2%	2%
	Spin & rotate	3%	2%	2%
Pencil	No motion	48%	25%	36%
	Bonding / e-Transfer	11%	8%	6%
	Rotation	40%	60%	52%
	Free motion	--	1%	1%
	Spin & rotate	2%	6%	5%

* The difference was found to be significant (p=0.000).
+ The difference was not found to be significant (p>0.05).
The three symbols represent the significance of each analysis conducted for K-Sketch, ChemSense, and Pencil, respectively.

III. Deeper understanding of animations through interviews

After students completed their animations, the majority (62%) were interviewed. In the interviews they were asked to explain their animations, whether they were able to show what they intended to show, the challenges they experienced, and their opinions about the software program they used. The answers were analyzed and interpreted in terms of three main categories: intention of motion in the animations, misconceptions conveyed in the animations, and the affordances of the software programs. Students' responses for the *Intention of motion in the animations* and *the affordances of the software programs* are discussed in the next section.

Misconceptions conveyed in the animations. When the animations and interviews were coded, analyzed and compared, it was found that some students showed some types of motion on purpose, revealing that they had specific misconceptions related to motion, such as spinning of nucleus and orbitals, vibration of protons and neutrons. Regardless of the type of software program they used, similar misconceptions were observed related to the type of motion of parts besides electrons. The percentage of students who had misconceptions were 21%, 17% and 14% in K-Sketch, ChemSense and Pencil, respectively. Figure 12 shows a student's animation depicting misconceptions related to the motion of parts.



(a) (b) (c)

Figure 12. Screenshots of the animations depicting misconceptions related to the motion of parts: (a) rotation of nucleus, (b) rotation of orbitals, (c) motion of protons and neutrons.

IV. Comparison of three different animation-developing software programs

Static and dynamic representations of mental models of students who used different software programs to generate animations were also compared by the Kruskal Wallis Test to check whether there was any difference between the groups. The results of the analysis showed that there was no statistically significant difference ($p>0.05$) between any of the features conveyed in static representations of mental models. On the other hand, depending on the affordances of the software programs, there were some differences observed in the animations, as grouped into two main categories: the type of atomic models represented in animations, and the use of color in the animations.

Type of atomic models represented in animations. The only significantly different ($p=0.019$) feature observed was the type of atomic models conveyed in animations. Although Bohr's model was still the most popular type of representation in all the groups (74%, 81% and 82% of the students in the K-Sketch, ChemSense, and Pencil groups, respectively, showed it in their animations), 24%, 14% and 17% of the students showed Modern Integrated Model in these groups, respectively. This result may suggest that K-Sketch enabled students to prepare such animations, as in Figure 7 (c), by providing them more freedom and flexibility in terms of motion options. On the other hand, ChemSense provided more suitable tools -- e.g., circles for students to generate Bohr-type atomic models. In addition, in the 7th grade Turkish middle school science curriculum (MEB, 2013), atomic models are first introduced by Bohr's Atomic Model, and are emphasized more than other types of atomic models throughout the rest of the science education curriculum.

Intention of type of motion in the animations. Immediately after learning a new program, students were asked to prepare an animation of an oxygen atom. Due to the variations in their experiences and capabilities with using a particular software program, some of them experienced technical difficulties, and therefore could not show what they intended to show. For instance, in the K-Sketch group, 14% of the students said that they showed the motion of orbitals because they couldn't show the motion of electrons; in the same group, 10% said they showed the rotation of orbitals because they believed orbitals were rotating with the electrons embedded in them. Similarly, in the ChemSense group, 3% of the students reported showing the motion of the nucleus unintentionally, whereas 6% of them declared that they thought the nucleus of the atom was also moving inside the atom as well as the electrons.

When the interviews were coded and analyzed, it was observed that even though there were some discrepancies between what students showed and intended to show, their intentions were mostly consistent with the coding of animations and matched to a good extent (93%) across all software programs. In general, the majority of students intended to show only the motion of electrons, but some students did intend to show other types of motion, such as motion of atoms, parts or zooming. Table 10 summarizes the types of motions shown in the animations and the intention of students for three different software programs.

Table 10. Percentage of students who used K-Sketch, ChemSense and Pencil, with respect to representations of types of motion in animations and their intentions to show each type of motion.

Type of Motion	Zooming	Atom	Bonding	Parts	Electrons	e- & others
K-Sketch (animation)	–	17%	1%	17%	47%	14%
K-Sketch (intention)	–	10%	–	5%	64%	21%
ChemSense (animation)	7%	13%	12%	4%	35%	28%
ChemSense (intention)	7%	9%	10%	4%	49%	17%
Pencil (animation)	–	19%	5%	2%	48%	23%
Pencil (intention)	4%	11%	2%	1%	71%	14%

Affordances of the software programs. When the students were asked whether they were able to show what they intended -- in other words, whether they were happy with their animations -- 78% in K-Sketch, 48% in ChemSense and 66% in the Pencil groups said they were able to depict what they intended to show. In addition, 23% in K-Sketch, 8% in ChemSense and 16% in Pencil groups said they would like to add a new motion to their animations. Even though some of them said that they were happy with their animations, they still wanted to modify their work either in terms of structure, or motion, or just the drawing. Table 11 shows the comparison of students' intentions to modify the animations they prepared.

Table 11.Comparison of students' intentions of modification of animations prepared in each software program

	Showed what they intended	Wants to add a new motion	Wants to refine motion	Wants to refine structure	Wants to refine drawing
K-Sketch	78%	23%	17%	25%	23%
ChemSense	48%	8%	8%	19%	21%
Pencil	66%	16%	9%	24%	21%

When the students were asked how they would modify the software program, they suggested modifications to enrich the structure and dynamics, as well as making the drawing or animating easier. As seen in Table 12, in all the software programs they wanted to modify the toolbar to facilitate making the drawings and animations. In addition, they wanted to give animations a more 3-D look in all of the software programs. In K-Sketch and Pencil, they wanted more options for geometrical shapes and colors, whereas in ChemSense there was no such need.

Table 12.Comparison of students' suggestions to improve each software program.

	Shape	Color	3-D	Modifying Toolbar	Modifying Motion Options
K-Sketch	36%	22%	17%	20%	1%
ChemSense	1%	–	14%	27%	7%
Pencil	32%	3%	14%	33%	3%

Use of color in the animations. When the animations prepared in different software programs were compared with respect to the use of color, the findings were similar. Color was mostly used to depict different parts and structures such as the nucleus as in Figure 10 (c), protons and neutrons as in Figure 12 (c), electrons as in Figure 12 (a), orbitals as in Figure 12 (b); or for color coding, such as electrons in different orbitals as in Figure 10 (b). Some animations, such as Figure 10 (a), did not use color at all. Special characteristics of the software programs enabled students use color for different purposes. For instance, more students in the ChemSense group used color for the nucleus, because students mostly placed the symbol for the oxygen atom at the center, as the nucleus, by using the Periodic table tool available in ChemSense, as seen in Figure 9 (c). Similarly, in Pencil, students used various effects, such as the brush available in the toolbar, to highlight electrons, as seen in Figure 9 (a). Table 13 summarizes the percentage of students who used color for different purposes in the animations.

Table 13. Percentage of students who used color for different purposes in the animations prepared in different software programs.

	No color	Nucleus	p/n	Electrons	Orbitals	Color coding
K-Sketch	22%	22%	27%	39%	15%	6%
ChemSense	26%	51%	13%	33%	5%	4%
Pencil	16%	43%	22%	68%	17%	8%

Conclusions

Understanding the nature of particles, atoms and molecules is a challenge for most students (Driver, 1985; Griffith & Preston, 1992, Talanquer, 2012). In various studies, students' mental models of the structure and dynamics of atoms were investigated through paper-pencil questionnaires and interviews (Cokelez & Dumon, 2005; Griffith & Preston, 1992; Nakioglu, 2003, 2008; Papageorgiou, et.al, 2016; Papaphotis & Tsaparlis, 2008; Taber, 2013b). However, the concept *atom* involves the dynamics of electrons; therefore, the medium used to display representations of mental models needs to include tools for displaying dynamics. Animation-developing software programs are essential tools to be used for K-12 science education because it provides the environment necessary for displaying dynamics, whereas paper-pencil and interviews are limited in their ability to represent dynamic features. Hence, this study aimed to investigate and compare high school students' static representations of mental models, which were displayed on paper, with dynamic ones depicted via animations.

This study provided several valuable findings that can contribute to the research and practice in chemistry education. These findings can be categorized into three parts:

(a) Student-generated animations may impact student learning.

When the initial static, dynamic, and final static representations of mental models were compared, the results of the analysis showed that there was significant difference (p=0.000) between the initial and final static representations of mental models in terms of the type of atomic models conveyed. Thus, it could be claimed that regardless of the software program used, students' representations of mental models of atomic structure significantly improved, suggesting that preparing animations as a modeling activity might have caused this change in students' mental models as they pass through an active cognitive and metacognitive stage (Schwarz et al., 2009). As Gilbert (2004) argued, mental models are not rigid, but open to change. Therefore, it could be suggested that generating animations as a modeling activity helps learners to improve their mental models of the atom. In addition, as suggested by Chi (2009), drawing is an active process that help students recognize their conflicting ideas and examine and correct them.

This study made use of one of the important strategies, models and modeling, which have been considered as essential components of science and science education due to their crucial role in scientific discovery and reasoning (Clement, 2000, Levy, 2013). Instead of using models as tools for demonstration (Williamson, 2008), students were asked to build their own models, which helped them improve and refine their mental models towards a more accurate understanding, as also suggested by other researchers (Lehrer & Schauble, 2006; Leenaars et al. 2013; Schwarz et al., 2009). One of the contributions of this study could be the comparison of static and dynamic representations of mental models in terms of critical attributes of the structure and dynamic of the atom, and to identify how creating dynamic models affects static representations of mental models in terms of these attributes.

In addition, student-generated animations effectively revealed students' prior understandings. Based on the codes that emerged, the comparison of mental models was done by considering two main types of features: *structure* and *dynamics*. The structural features included the type of atomic models and the models' representations of electrons, nucleus and orbitals. Among the three types of atomic models -- *symbolic, Bohr's and modern integrated models* -- Bohr's model was depicted the most frequently. These findings were found to be consisted with Nakiboglu (2003), who found that the majority of students having one kind of misconception were holding the *solar system model* (named Bohr's model in this study and in Justi and Gilbert, 2000)).

(b) Student-generated animations can be used as a powerful assessment tools.

i. Using one kind of animation-developing software program enabled students to incorporate dynamic features to their static representations of their mental models of the atom because students included dynamic features in their final static representations of mental models significantly (p=0.000) more than the initial ones.

Dynamic features -- in other words, motion -- can also said to be another significant finding of the comparison of static and dynamic representations of mental models. A significant difference in terms of *representation of motion* was found between the static and dynamic representations of mental models. This might be an expected result due to the difficulty of depicting motion on paper, but even when a storyboarding tool was provided, it was not very common for students to think about and represent motion. Therefore, the role of animation developing tools becomes prominent, because they provide the necessary medium to display motion. Additionally, students' initial and final static representations of mental models showed significant improvement (p=0.000) in terms of representing motion; therefore, creating animations may have helped students to include the notion of motion in their mental models. On the other hand, the type of motion shown in the animations was mostly rotation of electrons around the nucleus -- a solar system model -- which was again consistent with previous research findings (Nakiboglu, 2003; Taber, 2013b).

ii. Animations prepared by students revealed some misconceptions related to the dynamic features of the atom, which would be hard to detect on paper; these include the motion of the nucleus, protons and orbitals, or the atom itself, besides the motion of electrons.

As confirmed by the interviews, some of the animations were found to include misconceptions such as the spinning of the nucleus inside the atom, which would not be able to be determined through static drawings or explanations. Thus, animations were helpful in better understanding how students visualize the atom. Therefore, animation-developing software programs, such as K-Sketch, ChemSense, or Pencil may become important tools to integrate into science classes and could help science educators investigate how students model dynamic representations, behaviors, and processes.

(c) The comparison of three common software programs with different affordances revealed differences.

Although all the animation-developing software programs revealed similar results in terms of conveying and modifying representations of mental models of students, they had different affordances. Comparison of the programs showed that K-Sketch provided the most freedom for representing dynamics, and ChemSense provided more options for representing structural features. The majority of the students who used K-Sketch (78%) said they successfully showed what they intended to show, and 24% of them showed modern integrated models which are better represented when the program provides flexibility in representing motion. In comparison, only 48% of the students who used ChemSense said they showed what they intended, with 14% depicting a modern integrated model with the limited options for motion. In addition, 36% of the students who used K-Sketch and 1% of those using ChemSense suggested that adding geometrical shapes to the program, could help in constructing structures.

Limitations of the study

This study aimed to investigate and compare static and dynamic representations of mental models of atomic structure. Although they were called *mental models* or *representations of mental models,* these are students' *expressed mental models* (Gilbert, 1997) and may not necessarily be 'true' representations of mental models. In addition, even though the features of the representations of mental models were coded by two researchers and 95% agreement was reached in coding, they are limited to the researchers' understanding and interpretations; again, they may not be the real or actual representations of mental models. In some cases, the sophistication of the students' mental models may have been limited by the affordances of the animation-developing software programs. In addition, no delayed posttests were given in the study, so the changes in the mental models could reflect only a mediation, not necessarily a permanent change.

The students who attended the workshops were not randomly assigned; in fact they came from one school and one grade level in intact classes. Not being able to use random sampling might have an effect on the results.

Implications for teaching and learning

The role of models and modeling activities is crucial in science and specifically chemical education because models help learners to visualize and understand abstract concepts such as the nature of particles (Gabel & Sherwood, 1980; Gabel, Briner, &Haines, 1992). As technology advances, computer-based modeling, which better represents dynamics such as motion and interactions, is replacing concrete and static models. Although many animations and simulations are available for use in classroom and laboratory instruction, they may be limited for some specific topics, or for certain student needs. In this case, science teachers could easily use animation-developing software program to create their own unique animations for specific purposes and readily use them in their classes. K-Sketch, ChemSense and Pencil are easy to learn and provide freedom to the users. Besides using already existing physical models or animations as part of instruction, is it also helpful for students to build their own models, because the modeling processes may improve their meta-knowledge (Schwarz et al., 2009) and conceptual understanding (Lehrer & Schauble, 2006; Schwarz & White, 2005), and help them focus on the processes as well as the products of science (Leenaars et al. 2013). Animation-developing software programs are necessary tools for chemistry or science instruction, in general, because they allow students to create their own unique models in the form of animations so that teachers could assess students' understandings, including dynamics, and identify motion-related misconceptions that would be difficult to detect when using static paper-based models. In other words, teachers and instructors could use students' dynamic animated models for diagnosis and assessment purposes.

The nature of chemical phenomena involves understanding and relating chemistry at three levels: the macroscopic, symbolic, and the particulate (Johnstone, 1993, 2010; Taber, 2013). The particulate or submicroscopic level, perhaps the most important, includes abstract and invisible processes best explained via models. For this reason, if needed, the high school and introductory level chemistry curriculum could be reconsidered in the sense that the dynamics at the submicroscopic level and their connection to other two levels should be made apparent. Textbooks, supplementary materials, and student and teacher guides suggesting dynamic model-based activities should be developed and disseminated. In other words, helping students build their own dynamic models while developing the most accurate representations of mental models should become the standard. When computer-based modelling tools and animation-developing software programs are not available for the teachers to use in their classes, they can still incorporate dynamic modelling in terms of using games (Capps, 2008), dance (Mahaffy, 2004) and gestures (Gilbert, 2007) to teach processes and motion. In fact, it could be recommended to teachers to use diverse tools with different affordances, instead of using only one type, because each type of tool will bring a different benefit to students. In addition, it is important for instructors to consider the limitations of these software programs if they plan to use them for assessment. As revealed in the student interviews, students sometimes may show a motion unintentionally, due to the difficulties they may face in using the software program.

Considering the value of models and modeling in science education, their infusion into science teacher education will be inevitable. One way of doing this could be incorporating modeling in teaching methods courses and school training experiences. For instance, prospective teachers could be asked to include different kinds of modelling activities when they plan and teach science lessons. In addition, teaching methods courses could include animation-developing software, such as K-Sketch, and how to make use of it while teaching science. Exposure to modelling activities could make pre-service teachers more aware of the importance of modeling in teaching and learning science and chemistry. Last but never least, seminars and workshops emphasizing the importance of modeling in science and science education and different methods for incorporating modeling activities in science classes could be organized for in-service science teachers or practitioners. As science teachers start to adopt modeling activities by having their students build their own models using various dynamic computer-based tools such as K-Sketch, ChemSense and Pencil, academic research would reach into science classes via service teachers. This research identified how letting students create their own animated models can make their mental models more accurate. Thus, it could be claimed that this research contributes to science education by helping students refine and revise their mental models, thus, understandings of chemical phenomena. Today, almost all the high schools and colleges actively use information and communication technologies in science classes. Since animation-developing software programs, including K-Sketch, works both on tablets and personal computers, this research is relevant to science education and can easily be used in classroom teaching and learning both as a tool of instruction and assessment.

Implications for research

Software programs that allow students to create dynamic animations of their representations of mental models can be a powerful research tool. Students' representations of mental models in other chemistry concepts including motion and interactions such as chemical reactions, equilibrium, and electrolysis could be investigated. In addition, similar studies could be carried out in other fields of science education, and the effectiveness of using animation-developing software programs on eliciting and refining students' mental models for different contents -- e.g., physics, biology and astronomy -- could be investigated. As a future direction, an implementation for a longer period where students generate animations for a specific topic of chemistry such as gas laws could be designed, and how students develop and retain their mental models could be investigated. In addition, further research can be conducted to compare the differences between viewing the animations and going through the process of constructing them.

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