JOURNAL OF INTERACTIVE
MEDIA IN EDUCATION

Evaluating the Design and Development of the “Making Molecules” Simulation: Students’ Perceptions and Recommendations

ARTICLE

]u[ubiquity press

PAULINE SALIM MULJANA
JODYE I. SELCO

*Author affiliations can be found in the back matter of this article

ABSTRACT

Students perceive molecular bonding as an abstract concept; therefore, learning this concept seems uninteresting and difficult. A strategically designed learning object (LO), such as in the form of a simulation, can be used to help students acquire accurate mental images and build appropriate schema in addition to providing a concrete learning experience and encouraging knowledge construction. This paper presents an evaluation of the design and development of the *Making Molecules* simulation through students’ perceptions of the previous version and recommendations for improving a future version. Data were collected from two online chemistry courses ($N = 159$) through an anonymous online survey. Results suggest that students responded positively to the use of the simulation. They reported gaining a better understanding of molecular bonding through an interactive learning experience. One of their recommendations was to include more learning tasks related to complex molecules, expressing an interest in learning more about chemistry. This paper provides insights for educators and instructional designers regarding selection and/or design of an LO for optimizing student learning of complex topics.

CORRESPONDING AUTHOR:

Pauline Salim Muljana

California State University,
San Bernardino, US

Digital Promise, US

pauline.muljana@gmail.com

KEYWORDS:
Learning object; simulation; chemistry education; molecular bonding

TO CITE THIS ARTICLE:
Muljana, PS and Selco, JI. 2023. Evaluating the Design and Development of the “Making Molecules” Simulation: Students’ Perceptions and Recommendations. *Journal of Interactive Media in Education*, 2023(1): 1, pp. 1–16. DOI: https://doi.org/10.5334/jime.772

"Many [chemistry] students confuse the processes that involve chemical transformations with changes in the physical states backed by their senses, without making use of the scientific models," according to Silva et al. (2016: 387). At the core of this problem is that molecules are not visible even with a microscope, let alone a human eye. While chemists have devised laboratory methods of manipulating molecules, they use symbols to describe chemicals and their changes. Without understanding what all the symbols mean, students perceive molecules, their formation, and changes that occur to molecules as abstract, uninteresting, and difficult (Bayir 2014; Caglar et al. 2015).

There are multiple representations used in chemistry (i.e., macroscopic, sub-microscopic, and symbolic), which can help students comprehend the concept from different perspectives and visualizations in order to form an accurate description (Abdinejad et al. 2021; Johnstone 1982, 1991; Muljana et al. 2020; Talanquer 2011; Treagust, Chittleborough & Mamiala, 2003). Unfortunately, most textbooks display symbolic or two-dimensional representations, and therefore it can be difficult for students to understand the physical structure of molecules in three dimensions (Muljana et al. 2020). Using a learning object (LO), such as simulation, potentially enhances the learning of abstract chemical concepts by providing manipulable parts as well as multiple representations (Bayir 2014; Geselbracht & Reisner 2010) and multiple perspectives of the concepts (Wiley 2002). An LO is "any digital resource that can be reused to support learning" and can be designed to align with a specific learning outcome (Wiley, 2002: 6). Simulation, defined as a "computer-based model of a natural process or phenomenon that reacts to changes in values of input variables by displaying the resulting values of output variables" (de Jong & van Joolingen 2008: 457), is considered as a type of LO (South & Monson 2002). In this paper, we use the terms LO and simulation interchangeably.

While using an LO is potentially beneficial, it is crucial to investigate students' perceptions of using the LO for learning a topic. If there are any negative perceptions, it may hinder learning (Apostolou, Blue & Daigle 2009; Zamani-Miandashti & Ataei 2015). This paper presents an evaluation of the LO *Making Molecules: Dot Structures and Ionic Compounds*, which was intended to assist students in understanding how covalent molecules form using Dot Structure representations and how ionic compounds form using explicit charge representations. This paper contributes additional evidence to the existing literature and provides insights informing educators and instructional designers regarding the selection and/or design of an LO for enhancing student learning of complex topics. The following questions guided the evaluation:

- What were students' perceptions of using the LO for learning molecular-bonding concepts?
- What were students' recommendations about improving the LO to support learning?

LITERATURE REVIEW

Learning STEM-related subjects requires higher-order thinking skills, such as problem-solving, that can be accomplished through strategic instructional scaffolding (Caglar et al. 2015). The LO evaluated in this paper provides instructional scaffolding based on the published best practices and was deliberately designed to: (a) provide a concrete learning experience, (b) promote appropriate schema formation, and (c) encourage knowledge construction.

PROVIDING CONCRETE LEARNING EXPERIENCE

Novice learners perceive new information and approach problems differently than experts do (Nakhlah 1992). They do not recognize the meaningful organization and patterns of knowledge (Bransford et al. 2000), and they tend not to grasp what experts perceive. In learning chemistry, novices can misinterpret symbolic and even flat representations used in the textbooks. Novices may inaccurately understand the use of coefficients and subscripts (Nakhleh 1992). This misinterpretation or misconception may cause an inability to visualize molecular formation or changes. It is not a surprise that students as novices consider molecules, their formation, and changes as abstract, difficult-to-understand concepts (Abdinejad et al. 2021; Bayir 2014; Caglar et al. 2015).

Providing concrete experiences allows students to explore an abstract concept using their senses (Richey, Klein & Tracey 2011), highlighting the need for emphasizing an instructional strategy that provides realistic learning experiences, such as through concrete representations, so that learning can be experiential (Richey, Klein & Tracey 2011). This notion supports the use of physical models in STEM education to represent objects or processes of STEM-related concepts (Gustafson, Mahaffy & Martin 2015). For example, Eastwood (2013) designed a timed, game-like group activity, allowing students in groups to compete with one another in building molecules by using the physical models. Students in Eastwood's (2013) study enjoyed the activity and gained problem-solving skills, increasing their understanding of molecular bonding. While Eastwood's (2013) activity appears to be helpful in increasing students' interest and mastery of molecular formation, the use of physical models is mostly limited to the face-to-face learning environment. In an online learning environment, the representative models should be designed for flexible access without being constrained by geographical and temporal barriers. The digital LO we use in this evaluation includes a feature allowing students to build their own molecules so they will not rely on physical models.

In chemistry education, molecular representations are presented to students to provide a more concrete experience (Johnstone 1982, 1991; Talanquer 2011; Treagust, Chittleborough & Mamiala 2003). The three types of representation are (1) macroscopic, (2) sub-microscopic, and (3) symbolic. At the macroscopic level, students can observe the chemical reactions of bulk materials (e.g., an explosion). Atoms, molecules, electrons, and ions and the interactions among them are best described with sub-microscopic representations. Dot Structures or diagrams are sub-microscopic representations that help students visualize the sharing of electrons between atoms to form a molecule (Figure 1 provides an example). The symbolic-level descriptions are the least detailed, but simplest (e.g., H_2O). In learning about the chemical-bond formation, a failure to assimilate multiple types of representation can negatively impact students' comprehension (Abdinejad et al. 2021; Johnstone 1982, 1991; Linenberger & Holme 2014).

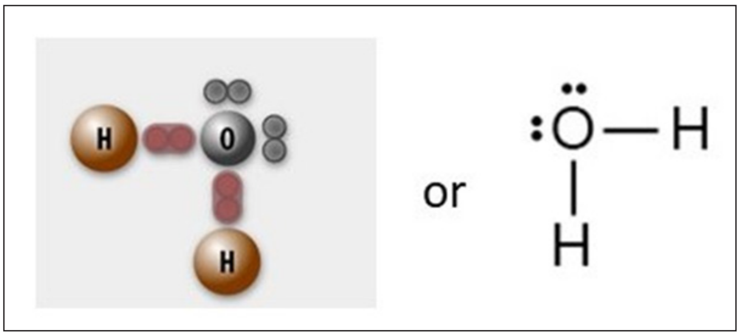

Figure 1 Two screenshots from the 'Making Molecules: Dot Structures and Ionic Compounds' LO.

Note: Both screenshots show Dot Structures. The one on the right is sometimes called the 'stick figure,' which is most common.

PROMOTING SCHEMA FORMATION

Knowledge is stored in the long-term memory, and a structure of this knowledge is called schema (Richey, Klein & Tracey 2011; Sweller 2008; Sweller, van Merrienboer & Paas 1998)—the plural form is schemata. The knowledge needed for undertaking the problem-solving process is organized in this schema. Solving problems demands specific ways of manipulating the knowledge components in the schema (Merrill 2002). As mentioned above, novices do not have this structure of knowledge, whereas experts have established it in their long-term memory through numerous years of experience (Bransford et al. 2000). Novices can fail to recognize the meaningful organization and knowledge patterns that the experts can (Bransford et al. 2000).

When students do not have the appropriate schema, they will maximize, even overload, their working memory during the learning process. When they attempt to interpret the concept of molecule formation, already perceived as complex, by using their limited (sometimes non-existent) schema, the effort required to process the information is consequently high (Castro-Alonso et al. 2021; Gustafson, Mahaffy & Martin 2011, 2015; Sweller 2010; Sweller, van Merrienboer & Paas 1998). Sweller (2008, 2010) suggests using the guidance fading effect to help novices form schema properly. Students can be presented with worked examples initially. As students gain more experience and expertise, worked examples can be gradually replaced by completion problems and eventually by full problems. In essence, the problems are sequenced in such a way so that students build appropriate schema gradually in the long-term memory based on appropriate and substantial guidance. Once the schema has been established, the guidance can diminish over time so that students can refer to their own long-term memory.

Because learning chemistry requires higher-order thinking, students need appropriate guidance and scaffolding (Caglar et al. 2015), which can be provided within a simulation (Correia et al. 2019). For example, Gustafson, Mahaffy and Martin (2011) employ strategic design elements in their simulation pertaining to particle movement in solids, liquids, and gasses. Understanding that working memory is limited; Gustafson, Mahaffy and Martin (2011) provided clear prompts, directing students to the crucial, relevant concepts. Findings suggest that students can retell how a particle moves in solids, liquids, and gasses. Another example of instructional guidance is by allowing students to generate their own image of the scientific process (Castro-Alonso et al. 2021). Castro-Alonso et al. (2021) highlighted a finding from the existing literature; students who drew demonstrated higher learning achievement than those who learned by summarizing and taking tests. However, the most effective scaffolding strategy for facilitating student-generated drawings is by providing "instructor-provided visualization" that allows students to complete the visualization and prevents students from generating an inaccurate image (Castro-Alonso et al. 2021: 1383).

ENCOURAGING KNOWLEDGE CONSTRUCTION

According to constructivism, learning is: (a) engendered through one's interpretation of experience, (b) "an active process occurring in realistic and relevant situations," and (c) "results from an exploration of multiple perspectives" (Richey, Klein & Tracey 2011: 130). Essentially, students make interpretations based on their prior experience, and this process is called the internal representation of knowledge (Duffy & Cunningham 1996; Ritzhaupt 2010). Students should be actively involved in the learning process, allowing them to construct knowledge rather than merely receive knowledge. A learning tool should encourage students' participation in, or contribution to, the knowledge construction process by including generative tasks that promote instructional experiences and facilitate students to generate their own content (Bannan-Ritland, Dabbagh & Murphy 2002). These generative tasks include activities that allow students to manipulate objects to enhance their learning experience (Bannan-Ritland, Dabbagh & Murphy 2002). Unfortunately, allowing students to manipulate only physical objects is not sufficient because students may only observe the surface process (Jaakkola & Nurmi 2008). Such a limitation can be addressed by using a digital LO to display the process that is not demonstrable physically (Jaakkola & Nurmi 2008; Resnick 1998; Triona & Klahr 2003). The LO evaluated in this paper virtually demonstrates the processes not visible to the naked eye and provides active manipulation activities.

Starting with a simpler, familiar context can help students bridge existing ideas with new topics to promote knowledge construction (Gustafson, Mahaffy & Martin 2011). Believing that students built their understanding by bridging new ideas with existing ideas, Gustafson, Mahaffy and Martin (2011) used a familiar context to help students make a new connection with the topics introduced in digital LOs. Students participating in their study were able to describe how particles—which the naked eye cannot see—moved in solids, liquids, and gases. Their findings highlight the role of the digital LO as a visual representation and an exploration tool to help prevent or correct misconceptions.

In another study, Gustafson and colleagues remained thoughtful about the process and role of scaffolding as aligned with constructivism (Gustafson, Mahaffy & Martin 2015). Two pedagogical agents were included in their digital LOs to scaffold students to construct explanations, clarify misconceptions, connect explanations with real-setting experiences, and review the concepts through various contexts (Gustafson, Mahaffy & Martin 2015). Another strategy for providing a scaffold within a simulation is the inclusion of feedback (Correia et al., 2019). Immediate feedback can help students compare their answers with the accurate ones to promote immediate learning gains (Corbett & Anderson 2001), especially when the concept is perceived as difficult (Shute 2008). A suitable format of feedback included in an LO or simulation can take the form of visual and text modes (Mayer & Moreno 2002).

USING A LEARNING OBJECT AS AN INTERVENTION

We consider the broad definition of an LO: "any digital resource that can be reused to support learning" (Wiley 2002: 6), and we pay attention to the different types of LOs. Based on the literature on LOs, Churchill (2007) lists the interpretations of an LO definition. The interpretations of LO vary; people interpret LO as any entity to support technology-mediated learning, a reusable digital resource to support and mediate learning, interactive practice, a learning component including measurement to address a specific learning outcome, a mental model, an interactive resource conveying one or more concepts, and a visual representation, among others (Churchill 2007). Synthesizing the interpretations, Churchill (2007) categorizes LOs into six types: (1) presentation, which is typically used to direct instruction and show presentation materials; (2) practice, which provides drill, practice, and feedback regarding a procedure; (3) simulation, which represents a real-life process; (4) conceptual models, which represent a key concept; (5) information, which presents information using multiple modalities; and (6) contextual representation objects, which provide explorative opportunities that include real-life scenarios and data collection.

The current learning problem encountered by chemistry students could stem from an inability to observe and manipulate entities and processes invisible to the naked eye. While attempting to understand the chemicals, their form, and changes, misconceptions can commonly happen (Nakhleh 1992). On top of this, students, as novices in the chemistry field, may not have the appropriate schema. Without an appropriate schema, they can quickly overload their working memory when learning the chemical processes unseeable by the naked eye and perceived as difficult. Therefore, students need to be scaffolded (Caglar et al. 2015). We saw an opportunity to design and develop an LO that serves as a simulation to represent real-life chemical processes and simultaneously allows students to practice, explore and receive feedback. The unique characteristics of digital LOs allow visualization of complex problems through multiple perspectives, provide learning scaffolds, and encourage exploration through manipulable parts (Geselbracht & Reisner 2010). Additionally, since LOs are flexible enough to revise (Ritzhaupt 2010), selecting the LO as an intervention strategy offers the low-maintenance characteristic that allows us to address future technical issues without spending laborious time.

The LO is suitable to address the learning difficulty of how atoms and ions combine to form molecules and compounds in chemistry courses. Informed by the literature above, we designed and developed an LO entitled *Making Molecules: Dot Structures and Ionic Compounds*. The LO contains design strategies, such as (a) a combination of at least two types of representations, e.g. sub-microscopic (allowing students to interact with chemistry entities that are unobservable by the naked eye) and symbolic (allowing students to make connections with the chemical formulae and diagrams in textbooks) to provide students with a concrete learning experience; (b) integration of Sweller's (2008, 2010) guidance fading effect by providing guided and then free-experiment activities to promote schema formation; and (c) provision of generative tasks, allowing students to create molecule models and encouraging knowledge construction.

METHOD

CONTEXT AND PARTICIPANTS

After acquiring approval from the Institutional Review Board at the university under study, we recruited participants who were students enrolled in two undergraduate online chemistry courses. We emphasized the voluntary nature of their participation; for example, their participation or non-participation would not affect their grades. We ensured anonymity; the survey did not include questions that asked for identifiable information. We further explained that if students decided to participate they could opt out at any point during the study. Additionally, clear instructions on how to participate and a consent form were included at the beginning of the survey.

The student participants (N = 159) were from two courses offered as a lower level and upper level because the LO might potentially be used by students with diverse prior knowledge. The first course was an upper-level general education (GE) course focusing on quantitative thinking in chemistry. This GE course had prerequisites of oral communication, written communication, critical thinking, math, life science, physical science, and a science laboratory course. Participants from this course (N_1 = 105) included 36 students (34.3%) who took more than enough chemistry courses to earn a minor in chemistry—a minor requires 30 semester units. Fifty students (47.6%) took just enough chemistry courses to earn a minor in chemistry. One student had not taken a college-level chemistry course. Eleven students (10.5%) took a year of General Chemistry and a few other chemistry courses. Six students (5.7%) had only taken a General Chemistry course. One student reported that the only previous chemistry in which they had enrolled was for non-STEM majors.

The second course was General Chemistry, an introductory course to the major that also satisfies a GE requirement. Participants from this course (N_2 = 54) included three students who had not taken any prior chemistry course. Forty-three students (79.6%) took chemistry in high school. Eight students (14.8%) took at least one college-level chemistry course. Two students (3.7%) enrolled in this course to satisfy a requirement for a physical science course. Three students (5.6%) reported that this course was recommended for their major. Forty-eight students (88.9%) took this course because it was required for their major. One student took this course due to an intrinsic interest in the subject.

INSTRUMENTATION

We created an anonymous questionnaire consisting of one or two multiple-choice questions about students' contextual information, seven 5-point Likert-scale (LS) items, and four open-ended (OE) questions inquiring about students' perceptions of the LO. Before survey dissemination, we piloted the survey with 64 chemistry students (Cronbach's α = 0.92). Additionally, several chemistry instructors reviewed the survey items and provided feedback regarding the language clarity and suitability with the course context. The items regarding contextual information allowed us to understand students' context and approximate their prior knowledge in chemistry. The LS and OE items were particularly purported to acquire students' insights regarding their perceptions of the visualizations or representations and perceived learning (e.g., to help us gain an understanding as to whether they implicitly reported a schema formation and knowledge construction). Table 1 lists the seven LS and four OE items used for the evaluation.

Table 1 The seven 5-point Likert-scale items and four open-ended items used in the questionnaire.

ITEM NUMBER	ITEM TYPE	STATEMENT
1	LS	I think using the Making Molecules simulation to learn about how atoms form molecules helped/would have helped me understand this concept.
2	LS	Using the Making Molecules simulation was an engaging way to learn/remember how atoms bond together to form molecules.
3	LS	Using the Making Molecules simulation taught/reminded me how many bonds each type of atom can form when combining to form molecules.
4	LS	I liked the interactivity of the Making Molecules simulation relative to my own pencil drawings on paper.
5	LS	The Making Molecules feedback on whether all electrons had partners or charges were balanced was useful.
6	LS	The Making Molecules simulation was a good addition to the course.
7	LS	The Making Molecules simulation was a good introduction to/reminder of molecular structure before the Colours module (which focused on structure of molecules).
8	OE	Complete the following statement – After using the Making Molecules simulation, I now realize that…
9	OE	Complete the following statement – While using the Making Molecules simulation, I really liked…
10	OE	Complete the following statement – After using the Making Molecules simulation, I can now visualize…
11	OE	Complete the following statement – In thinking about the Making Molecules simulation, I only wish that…

MATERIALS

We developed the LO using HTML5 canvas and the CreateJS JavaScript library to ensure compatibility with the latest browsers and multiple platforms (Muljana et al. 2020). It is worth mentioning that we searched the existing LOs and simulations before deciding to design our own LO. However, the existing LOs either used Adobe Flash that no longer worked for the latest browsers, displayed improper atoms' size, was not fully functional, did not show the bonds, or did not provide active manipulation activities (Muljana et al. 2020). At the time of writing this paper, we searched again, but the LOs we found had similar limitations. Such limitations would hinder us from correcting students' misconceptions, providing accurate multiple representations, and offering meaningful active manipulation activities.

The visualization features within this LO were deemed crucial notably because most physical models did not include the lone pairs of electrons, but their presence dictates molecular properties. Therefore, the LO included a feature allowing students to manipulate the chemistry objects (e.g., drag and drop). Also, feedback plays an imperative role in providing a scaffold to students in a simulation (Correia et al. 2019). In addition to sequencing the activities, the LO includes feedback that students can request. They can use the feedback to check the accuracy of their answer and compare it with the stick diagram. The generative tasks integrated in the LO promote the optimal use of students' prior knowledge and contribution in the knowledge construction, bridging the prior knowledge and new information (Bannan-Ritland, Dabbagh & Murphy 2002).

The LO included: (1) Introduction tab, presenting the purpose and instruction; (2) Molecule Builder tab, presenting both guided activities (Figure 2) and free-experiment mode for connecting electrons between atoms to form molecules (Figure 3); and (3) Ionic Compounds tab, presenting a free-experiment mode for connecting ion charges to form ionic compounds (Figure 4). Immediate feedback was provided, allowing students to check the answer accuracy and compare their answer with the chemical structure diagram. Further details of the LO design process and preliminary results of the design evaluation have been published as a design case (Muljana et al. 2020). The LO also includes an accessible version that was tested separately outside this evaluation phase. The accessible version was designed and developed purposely to display high contrast colors (which were also incorporated in the regular version) and to change the mouse-driven commands to be compatible with screen readers.

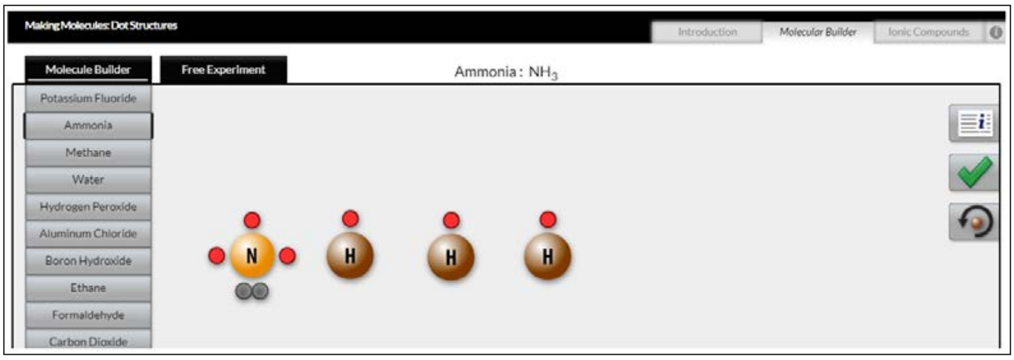

Figure 2 Guided activities within the 'Molecular Building' section.

Note: Guided activities are the initial exercise given to students via a drop-down menu of pre-programmed chemical compounds. It presents chemical compounds listed in order by increasing difficulty. In this figure, ammonia has been selected; students must connect the atoms correctly to form ammonia.

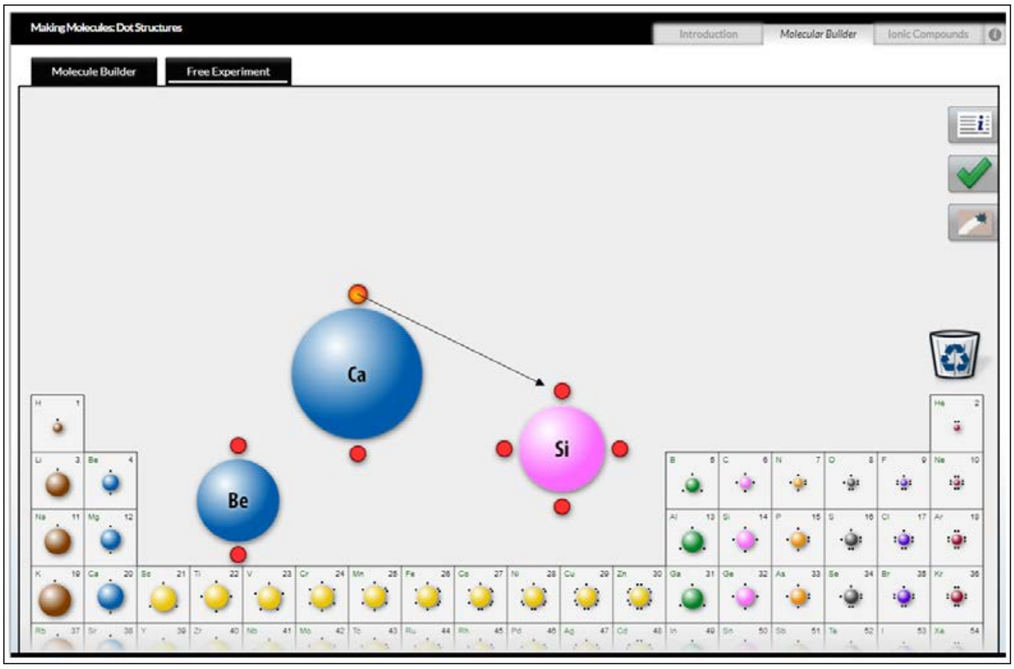

Figure 3 The free-experiment mode within the 'Molecule Builder' section.

Note: In a free-experiment mode, students select elements from the periodic table frame and build a molecule by connecting the selected elements. By this time, students have already gained fundamental expertise through the earlier guided activities.

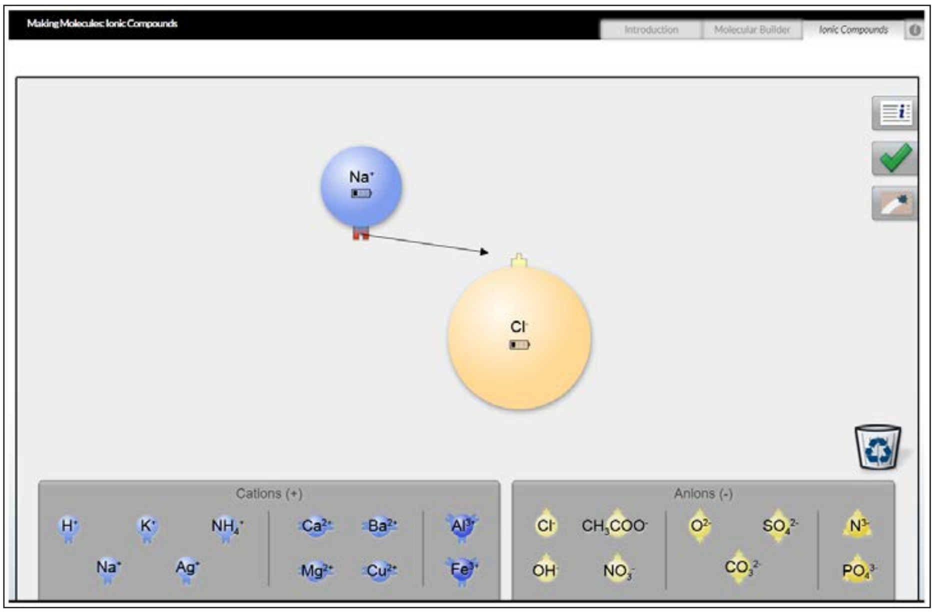

Figure 4 The free-experiment mode within the 'Ionic Compounds' Section.

Note: In the upper-level free-experiment activities, students can select ions from the palette and create ionic compounds by connecting the selected ions.

PROCEDURES

The instructor assigned the students to use the LO as part of a lesson. In the upper-division GE course, it was mostly a review in preparation for a lesson on chemical structure and the structure's function in the absorption of light. In General Chemistry, visualization and ideas of how molecules are constructed are the bedrock of most of the rest of the content in the year-long course. In both courses, the LO served as a learning tool to reinforce the foundational ideas of the course topics. Before assigning the students to use the LO, the instructor provided instructions on where to find the LO, demonstrated use of the LO, and described the technical requirements. Students had to complete 13 *pre-programmed* chemical compounds, which were the guided activities within the Molecule Builder tab (Figure 2). Next, they additionally completed the free-experimental activities within the same Molecule Builder tab (Figure 3); they were asked to create six free-experimental molecules through this phase. Individually, they took screenshots of the additional molecules and submitted the images to the learning management system (LMS). While the LO provided immediate feedback regarding the answer accuracy, the instructor provided constructive and motivating feedback regarding students' performance, along with a grade. The instructor then asked the students to share their experience of using the LO through the anonymous questionnaire.

DATA COLLECTION AND ANALYSIS

The instructor administered the online, anonymous questionnaire through the LMS after students used the LO as part of a lesson. Data analysis of survey responses took place through a few steps. The internal consistency was computed before conducting the descriptive statistics on the results of the Likert-scale items. Cronbach's alpha was 0.81, suggesting good reliability.

We took the thematic analysis approach (Braun & Clarke 2006) to search for patterns or themes in the open-ended responses. We read the students' open-ended responses several times to immerse ourselves in their responses. Next, the first author conducted an initial coding to answer the second evaluation question. Then, she searched for patterns by grouping the codes into themes. At the next phase, the second author reviewed all codes, themes, and the relationship between the codes and themes. While reviewing, she assisted in re-thematizing the codes and re-labelling each theme necessarily. When the codes and themes were re-reviewed, both authors discussed and resolved any disagreements until the themes were finalized.

RESULTS

STUDENTS' PERCEPTIONS OF USING LO

Likert-Scale Items

Descriptive statistical analysis for the seven Likert-scale items was performed to acquire students' perception of the LO, as displayed in Table 2. More than 85% of the students "strongly agree” or “agree” that using the LO helped them understand the concept (*M* = 4.12, *SD* = 0.53). About 90% of the students “strongly agree” or “agree” that using the LO was an engaging way to learn how atoms bond to form molecules (*M* = 4.29, *SD* = 0.67). More than 85% of the students “strongly agree” or “agree” that the LO reminded/taught them how many bonds each type of atom can form (*M* = 4.11, *SD* = 0.76). About 72% of students liked the interactivity of the LO relative to their own pencil drawings (*M* = 3.80, *SD* = 0.94).

Table 2 Results from the Likert-scale items.

Note: Cronbach α = 0.81. *N* = 159.

STATEMENT	STRONGLY AGREE *N* (%)	AGREE *N* (%)	NEITHER AGREE NOR DISAGREE *N* (%)	DISAGREE *N* (%)	STRONGLY DISAGREE *N* (%)	*M*	*SD*
I think using the Making Molecules simulation to learn about how atoms form molecules helped/would have helped me understand this concept.	50 (31.45%)	89 (55.97%)	12 (7.55%)	5 (3.14%)	3 (1.89%)	4.12	0.82
Using the Making Molecules simulation was an engaging way to learn/remember how atoms bond together to form molecules.	63 (39.62%)	83 (52.20%)	10 (6.29%)	3 (1.89%)	0 (0%)	4.29	0.67
Using the Making Molecules simulation taught/reminded me how many bonds each type of atom can form when combining to form molecules.	49 (30.82%)	84 (55.83%)	20 (12.58%)	6 (3.77%)	0 (0%)	4.11	0.76
I liked the interactivity of the Making Molecules simulation relative to my own pencil drawings on paper.	34 (21.38%)	81 (50.94%)	26 (16.35%)	15 (9.43%)	3 (1.89%)	3.81	0.94
The Making Molecules feedback on whether all electrons had partners or charges were balanced was useful.	47 (29.56%)	81 (50.94%)	23 (14.47%)	7 (4.40%)	1 (0.63%)	4.04	0.82
The Making Molecules simulation was a good addition to the course.	60 (37.74%)	72 (45.28%)	23 (14.47%)	4 (2.52%)	0 (0%)	4.18	0.77
The Making Molecules simulation was a good introduction to/reminder of molecular structure before the Colours module (which focused on structure of molecules).	53 (33.54%)	79 (49.69%)	17 (10.69%)	7 (4.40%)	2 (1.26%)	4.10	0.85

Students perceived the usefulness of immediate feedback; about 80% of students expressed “strongly agree” or “agree” (*M* = 4.04, *SD* = 0.82). When students were asked whether the LO was a good supplement to the course, about 83% of the students rated “strongly agree” or “agree” (*M* = 4.18, *SD* = 0.77). Students also believed that the LO was an excellent introduction to or reminder of molecular structure; 83% of students selected “strongly agree” or “agree” (*M* = 4.10, *SD* = 0.83).

Open-Ended Items

The open-coding and pattern-thematizing analyses yielded five themes regarding students’ further perceptions of the LO (see Table 3).

Table 3 Categories, examples (codes), and representative quotes from the open-ended responses.

CATEGORY	EXAMPLE	FREQUENCY OF MENTIONS	REPRESENTATIVE QUOTE
Students were able to visualize the molecular entities and molecular bonding	Representation of molecular bonding process	104	“… in order to make an ionic compound, there can be no unbalanced charges left. Likewise with the molecules, there can be no left over unbonded electrons in order to have a molecule made.”
	Representation of atoms, molecules, valence electrons	76	“I can now visualize how different atoms and ions fit together instead of just seeing the symbols for the atom or ion written next to each other.”
	Characteristics of ionic and covalent compounds	45	“I can now visualize the atoms and their charges and be able to cancel out the charges to be able to balance them.”
	Approximated size and ratio	24	“The relative sizes of the atoms, and that the amount of potential bonds per atom are already given.”
	Number of electrons for each atom	21	“I now realize that a helium ion can stand on its own without bonding to something else, though the simulation does not allow for the helium ion to bond to anything else.”
	Extended visualization to macroscopic properties	15	“There was a list of common ionic compounds used in the laboratory, so I can try building out the salts or liquids commonly used.”
	Recognition of multiple representations being used	5	“I can now visualize the structures of some molecules and/or compounds and how double/triple [bonds] look in the stick diagrams.”

(Contd.)

CATEGORY	EXAMPLE	FREQUENCY OF MENTIONS	REPRESENTATIVE QUOTE
Students were able to enhance their understanding of the concept	Valuable learning aid	32	"It is actually pretty simple after learning and understanding the material. At first it was definitely intimidating but not anymore."
	Optimizing learning process	26	"I wish many more chemistry classes on campus required this simulation due to its usefulness!"
	Giving meaningful, immediate feedback	22	"I also really liked that it explains why you got it incorrect or even gives hints rather than just saying wrong."
	Providing a new perspective toward existing comprehension	11	"[...] molecules can connect in many different ways and still use all the unpaired electrons. This can make many different compounds that have the same formula, just connected differently."
	Encouraging critical thinking	9	[I like] the interactive feedback and the ability to make my own compounds that weren't listed. This allowed me to critically think about the structures of the chemical compounds."
Students were encouraged to self-experiment while learning the concept	Making one's own molecules	26	"While using the making molecules simulation I really liked the free experiment tab, because it allows you to play around and create a variety of different molecules."
	Manipulating molecules	10	"I was able to manipulate the simulation and use the various options to understand the steps in making the molecules."
Students felt motivated to learn more	Desire to acquire more information about the compounds created	14	"[I wish] it would tell me the name of the molecule I constructed in the free experiment when I go to check my answer, that way you can play with different molecules to see what they make."
	Desire to learn more about chemistry	7	"... to learn more thing[s] about the chemistry in real life."
	Enjoyment of learning the concepts	4	"I now realize that it's no[t] as challenging as I thought."
	Desire to have more time to learn	3	"[I wish] I could have more time to do research about molecules connections."
Students perceived the usability of the LO	Interactive and intuitive	46	"I really liked how simple the program is. I wish we had used something similar in high school. The interactiveness of the program would have been nice to have."

Students Perceived an Ability to Visualize the Molecular Entities and Bonding

Students could simply visualize the molecular-bonding process (104 mentions) as well as atoms, molecules, and valence electrons (76 mentions). They also expressed that they understood the characteristics of ionic and covalent compounds (45 mentions). Additionally, they perceived the size and ratio of the chemistry entities (24 mentions) and the number of electrons for each atom (21 mentions). After using the LO, they could "visualize how different atoms and ions fit together" in their head when looking at a symbolic representation.

Furthermore, they could extend the visualization to macroscopic properties (15 mentions), such as "common ionic compounds" and "the structure of useful chemicals" they used in the laboratory. Some students recognized the use of multiple representations within the LO (5 mentions). A student, noticing the use of symbolic and microscopic representations, commented that "...the molecular formula was written out and the ball-and-stick model was also visible for comparison ...."

Students Perceived an Enhancement in their Understanding

Students perceived the LO as a valuable learning aid (32 mentions) that optimized their learning process (26 mentions). Unsurprisingly, they perceived the molecular-bonding concepts as "simple" and not "intimidating." The immediate feedback provided was meaningful (22 mentions) instead of simply marking their right or wrong answer. The LO provided a new perspective on existing comprehension (11 mentions); they realized the key points they did not understand before using the LO. Several students felt encouraged to use their critical thinking (9 mentions), expressing how the process of connecting electrons was fundamental. Once they gained this fundamental understanding, they were able to create their own molecules by applying the molecular-bonding principles.

Students Felt Encouraged to Self-Experiment

The LO encouraged engaging, hands-on activities. Unsurprisingly, students enjoyed making their own molecules (26 mentions) that they "had not seen or used before". Additionally, they could manipulate the molecules (10 mentions) to make "them bond differently".

Students Felt Motivated to Learn Further

While molecular bonding is commonly perceived as difficult, students participating in this evaluation desired to learn more. For example, they wanted to acquire more information about the compounds they created in the LO (14 mentions), being curious about "the properties … and any other interesting facts" about the molecules they made. They expressed a desire to learn more about chemistry (7 mentions), either in a future class or in real life. Additionally, they enjoyed learning the concepts using the LO (4 mentions) and wished to have more time to learn (3 mentions); put simply, they had fun learning and did not mind spending more time with the LO.

Students Perceived the LO Usability

It was interactive and intuitive at the same time (46 mentions). They recognized the "simplicity," ease of use, and "intuitiveness." The LO provided "a very simple way to understand" the molecular-bonding process.

Recommendations for Improving LO

There were suggestions for improvements (see Table 4). Students wished for an enhancement of the molecular representations (57 mentions), such as by making the geometries more accurate; one student "struggled trying to form rings". Incorporating a more realistic "3D version" and enhancing "the bond angles" would improve the LO. They would like additional learning tasks for practicing on complex molecules (27 mentions); while chemistry has been perceived as complex, students however asked for "a wider range of complex molecules" such as triple bonds. They wanted "a challenge section", allowing them to solve "more difficult problems".

Table 4 Examples and representative quotes related to recommendations for improving LO.

EXAMPLE	NUMBER OF MENTIONS	REPRESENTATIVE QUOTE
A need for enhancing the representations	57	"It would have been nice if the geometries of the molecules were accurately depicted."
A need to include more learning tasks related to complex molecules	27	"[…] there were more exercises for harder molecular structures. Also, it would be nice to add the ability to create a benzene ring so that this simulation can benefit people at many levels of chemistry simultaneously."
A need for improving the usability	23	"I only wish that you didn't have to restart the whole molecule if you messed up. I wish there was a back button or a button to erase one bond."
A need for improving the instructions/ directions	9	"[I wish] some of the instructions were clearer because I was at first confused on how to make ionic bonds in the simulation."
A need for adding other features	8	"In thinking about the making molecules simulation, I only wish that there were examples shown and worked out prior to you completing the activity rather than just a set of directions[…]."

Students noted that the usability could be improved (23 mentions), such as by providing an undo button. In the previous LO version, they had "to restart the whole molecule" when they needed to simply "erase one bond." Instructions could also be improved (9 mentions) as some students were confused about how to conduct a learning task regarding ionic bonds. Some students expressed a need to add other features (8 mentions). Worked-out examples would enhance their understanding and serve as supplemental instructions. Videos could provide additional explanations, and sound effects would make learning "more fun".

DISCUSSION

This paper presents an evaluation of a simulation by examining students' responses about using the LO to learn about molecular bonding topics and their recommendations for future improvements. Our findings suggest that a simulation may be suitable for supplementing traditional instructional strategies and may yield a positive learning experience, resonating with what Wolgin et al. (2005) and Correia et al. (2019) described in their work.

Novice students may not be able to conceptualize molecular formation without a representation aid and object manipulation (Eastwood 2013; Muljana et al. 2020). Molecules are not observable through the naked eye; chemists use symbols to represent chemicals and their changes. Unsurprisingly, students perceive them as abstract. However, our findings suggest that students can visualize how atoms bond, compare compounds through multiple representations, and perceive the molecules' atomic ratios and sizes after using the LO. The multiple representations used in the LO may provide an explanation regarding these findings. Existing literature suggests the use of multiple representations in chemical education to promote students' understanding from different perspectives and visualizations accurately (Abdinejad et al. 2021; Johnstone 1982, 1991; Muljana et al. 2020; Talanquer 2011; Treagust, Chittleborough & Mamiala 2003), and the students' responses in our evaluation are aligned with this literature.

Additionally, students appreciate manipulating molecules and building their own molecules. They appear to comprehend an abstract idea and seem to incorporate their experiences into the LO activities. Echoing Jaakkola and Nurmi (2008), an LO may include concrete, hands-on activities for students to gain a profound understanding regarding complex processes. Therefore, students can use their senses, instead of solely relying on abstract reasoning (Richey, Klein & Tracey 2011). Our findings have validated that utilizing a well-designed LO can provide motivating and engaging concrete learning experiences (Alessi & Trolip 2001). As expected, students in our evaluation express that they enjoy the activities within the LO and perceive an understanding of the concepts.

When learning chemistry, novices may inaccurately understand coefficients and subscripts, which may cause a misinterpretation about the concept and hinder their comprehension of molecular formation or changes (Nakhleh 1992). Students in our study perceive that the LO enhanced their learning and critical thinking. They also note in the survey—both in the Likert-scale (item 3; $M = 4.11$, $SD = 0.76$) and open-ended (11 mentions) responses—that the LO is a helpful learning tool to remind them about chemical bonding and gives a new perspective toward existing knowledge about the concept, in line with previous studies (Avramiotis & Tsaparlis 2013; Correia et al. 2019). It is possible that these students have a misconception and then are reminded about accurate molecular bonding and changes. Students may experience new perspectives about this concept, and it is possible that their misconception is clarified after using the LO. This perspective change may suggest that inaccurate prior knowledge structure may have been reformed to an appropriate schema.

To help students form appropriate schema, the LO used in this evaluation includes relevant information and content to prevent students from performing excessive efforts on working memory, which resonates with Sweller, van Merrienboer and Paas (1998) and with Gustafson, Mahaffy and Martin (2015). Another strategy is sequencing the learning tasks properly, such as by incorporating the guidance fading effect where the guided activities or information appear initially; then, when students have already gained a mastery, more complex problems can be presented (Sweller 2008, 2010). In our context, the LO presents the guided activities before the free-experimental activities. Following Mayer and Moreno's (2002) suggestion, feedback in visual and text formats is provided to allow students to compare their own answers with the accurate answer. Our results are consistent with the existing research that simulation-based learning can yield a successful learning experience when proper instructional scaffolding and feedback are incorporated (Correia et al. 2019).

Promoting knowledge construction starts from a simpler context to help students bridge the existing knowledge with the new topics (Gustafson, Mahaffy & Martin 2011). Such a strategy can be used to scaffold students so that the guidance manifested in the LO addresses misconceptions and connects explanations with real experience (Gustafson, Mahaffy & Martin 2015). Additionally, knowledge construction involves students' active participation in the learning experience; essentially, they are considered as the designers of their own learning

(Bannan-Ritland, Dabbagh & Murphy 2002). The students evaluating the LO note the value of the self-experimental activities. The self-experimental activities within the LO allow students to design their own molecules. After performing these hands-on activities, students wish for more complex molecules. It appears that the students are interested in solving more problems and learning more about the topic afterward. This echoes Bannan-Ritland, Dabbagh and Murphy (2002); a learning aid like this LO may include generative tasks to promote the optimal use of students' own knowledge and contribution in the knowledge construction. When the learning process that helps students construct knowledge is promoted, students are willing to learn more and proactively ask for more advanced problems, which they have expressed as a recommendation for improving the LO.

IMPLICATIONS

The current paper aimed to investigate students' perceptions of using an LO that was developed to follow research-based design strategies learned from the literature review. Because many students still struggle to learn chemistry (Abdinejad et al. 2021), it highlights the significance of our LO in supporting the learning of all students. Therefore, they can enjoy a STEM subject, feel motivated to learn further, and persist. The LO serves as a learning aid to assist students in understanding how covalent molecules form using Dot Structure representations and how ionic compounds form using explicit charge representations.

The bulleted list below includes practical implications, contributing additional evidence to the existing literature and providing insights to educators and instructional designers.

- ***Providing a concrete learning experience***
  - Use visual representations to allow students to explore the topics using their senses.
  - Integrate strategies relevant to the subject matter. For chemistry education, it is common to use multiple representations (e.g., macroscopic, sub-microscopic, and symbolic) to help students synthesize different perspectives of the topics into accurate descriptions (Abdinejad et al. 2021; Johnstone 1982, 1991; Muljana et al. 2020; Talanquer 2011; Treagust, Chittleborough & Mamiala 2003).
  - Provide hands-on, engaging activities. Therefore, students do not establish their understanding based on an abstract interpretation (Richey, Klein & Tracey 2011).
- ***Promoting schema formation***
  - Sequence the content based on the complexity level. The initial topic is used as a foundation for mastering the subsequent topics.
  - Integrate guidance fading effect. Worked examples and complete guidance appear at the beginning and are gradually lessened (Sweller 2008, 2010). Therefore, students establish an accurate foundation schema suitable for carrying out the subsequent, more complex learning tasks (Muljana et al. 2020). If the learning activity involves student-generated drawing, it is important to include an instructor-provided visualization as an initial guide or example (Castro-Alonso et al. 2021).
  - Give clear prompts to direct students' attention to the crucial, relevant concepts (Gustafson, Mahaffy & Martin 2011).
  - Provide immediate feedback so any inaccurate interpretation about the topic can be corrected sooner.
- ***Encouraging knowledge construction***
  - Associate the concepts that have been perceived as abstract with real-setting experience.
  - Include generative learning tasks to allow students to construct knowledge by generating their own content (e.g., allowing them to draw or design), exploring, and manipulating objects (Bannan-Ritland, Dabbagh & Murphy 2002).
  - Use relevant and familiar contexts to help students bridge their existing knowledge with new ideas (Gustafson, Mahaffy & Martin 2011).

LIMITATIONS, FUTURE RESEARCH OPPORTUNITIES, AND IMPROVEMENT

We recognized several limitations within this paper. The focus is specific, and it excludes the learning achievement variable. A future investigation may consider this variable by including pre- and post-tests to examine knowledge transfer and retention. It is also worth including student backgrounds and characteristics. Therefore, the relationship between student backgrounds, characteristics, perceived learning, and learning achievement can be further explored.

Despite the limitations, this paper overall provides insights informing educators and instructional designers regarding selection and/or design of an LO for optimizing student learning of complex topics, such as those commonly found in STEM programs. If the LO is well-designed according to the research-based design strategies found in the literature, it can potentially increase STEM learning for all students. The research-based design strategies manifested in our LO provide insights to other educators and instructional designers who intend to design and develop their own LO to promote the learning of complex topics.

As we were writing this paper, the LO revisions were underway to address students' recommendations. The updated LO addresses all the students' suggestions including the ability to form rings, triple bonds, the ability to undo the last step, and to use more than 12 atoms. It is also simpler to use as it is based on clicking on atoms to connect them instead of dragging an arrow from one connection site to another. Instructors can provide additional worked examples to help guide students with limited prior knowledge. The updated LO is free to use and available at https://elearning.cpp.edu/learning-objects/making-molecules/. Overall, the LO and this paper contribute to the practices of promoting STEM learning for all and add scholarly discussion to the existing literature. Particularly, chemistry educators who teach molecular bonding and ionic compounds can use the LO without any cost, potentially impacting students globally.

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR AFFILIATIONS

Pauline Salim Muljana orcid.org/0000-0003-0668-9083
California State University, San Bernardino, US; Digital Promise, US

Jodye I. Selco orcid.org/0000-0003-0795-4467
California State Polytechnic University, Pomona, US

REFERENCES

Abdinejad, M, Talaie, B, Qorbani, HS and **Dalili, S.** 2021. Student perceptions using augmented reality and 3D visualization technologies in chemistry education. *Journal of Science Education and Technology*, *30*(1), 87–96. DOI: https://doi.org/10.1007/s10956-020-09880-2

Alessi, SM and **Trollip, SR.** 2001. *Multimedia for learning: Methods and development* (3rd ed). Boston: Allyn and Bacon.

Apostolou, B, Blue, MA and **Daigle, RJ.** 2009. Student perceptions about computerized testing in introductory managerial accounting. *Journal of Accounting Education, 27*, 59–70. DOI: https://doi.org/10.1016/j.jaccedu.2010.02.003

Avramiotis, S and **Tsaparlis, G.** 2013. Using computer simulations in chemistry problem solving. *Chemistry Education Research and Practice*, *14*(3), 299–311. DOI: https://doi.org/10.1039/C3RP20167H

Bannan-Ritland, B, Dabbagh, N and **Murphy, K.** 2002. Learning object systems as constructivist learning environments: Related assumptions, theories, and applications. In: Wiley, DA, (ed.), *The instructional use of learning objects*. Bloomington, IN: Agency for Instructional Technology and Association for Educational Communications & Technology. pp. 61–97.

Bayir, E. 2014. Developing and playing chemistry games to learn about elements, compounds, and the periodic table: Elemental periodica, compoundica, and groupica. *Journal of Chemical Education, 91*(4), 531–535. DOI: https://doi.org/10.1021/ed4002249

Bransford, J, Brown, A, Cocking, R, Donovan, M and **Pellegrino, J.** 2000. *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academic Press.

Braun, V and **Clarke, V.** 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. DOI: https://doi.org/10.1191/1478088706qp063oa

Caglar, F, Shekhar, S, Gokhale, A, Basu, S, Rafi, T, Kinnebrew, J and **Biswas, G.** 2015. Simulation modelling practice and theory cloud-hosted simulation-as-a-service for high school STEM education. *Simulation Modelling Practice and Theory*, *58*(2015), 255–273. DOI: https://doi.org/10.1016/j.simpat.2015.06.006

Castro-Alonso, JC, de Koning, BB, Fiorella, L and **Paas, F.** 2021. Five strategies for optimizing instructional materials: Instructor- and learner-managed cognitive load. *Educational Psychology Review*, *33*(4), 1379–1407. DOI: https://doi.org/10.1007/s10648-021-09606-9

Churchill, D. 2007. Towards a useful classification of learning objects. *Educational Technology Research and Development*, *55*(5), 479–497. DOI: https://doi.org/10.1007/s11423-006-9000-y

Corbett, AT and **Anderson, JR.** 2001. Locus of feedback control in computer-based tutoring: Impact on learning rate, achievement and attitudes. In *Proceedings of ACM CHI 2001 Conference on Human Factors in Computing Systems*. Association for Computing Machinery Press. pp. 245–252. DOI: https://doi.org/10.1145/365024.365111

Correia, AP, Koehler, N, Thompson, A and **Phye, G.** 2019. The application of PhET simulation to teach gas behavior on the submicroscopic level: Secondary school students' perceptions. *Research in Science and Technology Education*, *37*(2), 193–217. DOI: https://doi.org/10.1080/02635143.2018.1487834

De Jong, T and **van Joolingen, WR.** 2008. Model-facilitated learning. In: Spector, JM, Merrill, MD, van Merrienboer, J and Driscoll, MP, (eds.), *Handbook of research on educational communications and technology* (3rd ed). New York, NY: Routledge. pp. 457–468.

Duffy, TM and **Cunningham, DJ.** 1996. Constructivism: Implications for the design and delivery of instruction. In: Jonassen, D, (ed.), *Handbook of research for educational communications and technology*. New York, NY: Macmillan. pp. 170–198.

Eastwood, MM. 2013. Fastest fingers: A molecule-building game for teaching organic chemistry. *Journal of Chemical Education*, *90*(8), 1038–1041. DOI: https://doi.org/10.1021/ed3004462

Geselbracht, MJ and **Reisner, BA.** 2010. Inorganic chemistry learning objects for use in the general chemistry curriculum. *Journal of Chemical Education*, *87*(7), 756–757. DOI: https://doi.org/10.1021/ed100366m

Gustafson, B, Mahaffy, P and **Martin, B.** 2011. Using digital learning objects to introduce students to the nature of models and the nature of matter. *Journal of Computers in Mathematics and Science Teaching*, *30*(4), 355–387. https://www.learntechlib.org/primary/p/36083/.

Gustafson, B, Mahaffy, PG and **Martin, B.** 2015. Guiding age 10–11 students to notice the salient features of physical change models in chemistry digital learning objects. *Journal of Computers in Mathematics and Science Teaching*, *34*(1), 5–39. https://www.learntechlib.org/primary/p/114412/.

Jaakkola, T and **Nurmi, S.** 2008. Fostering elementary school students' understanding of simple electricity by combining simulation and laboratory activities. *Journal of Computer Assisted Learning*, *24*(4), 271–283. DOI: https://doi.org/10.1111/j.1365-2729.2007.00259.x

Johnstone, AH. 1982. Macro- and micro-chemistry. *Social Science Review*, *64*, 377–379.

Johnstone, AH. 1991. Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*(2), 75–83. DOI: https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Linenberger, KJ and **Holme, TA.** 2014. Results of a national survey of biochemistry instructors to determine the prevalence and types of representations used during instruction and assessment. *Journal of Chemical Education*, *91*(6), 800–806. DOI: https://doi.org/10.1021/ed400201v

Mayer, RE and **Moreno, R.** 2002. Aids to computer-based multimedia learning. *Learning and Instruction*, *12*(1), 107–119. DOI: https://doi.org/10.1016/S0959-4752(01)00018-4

Merrill, MD. 2002. Knowledge objects and mental-models. In: Wiley, DA, (ed.), *The instructional use of learning objects*. Bloomington, IN: Agency for Instructional Technology and Association for Educational Communications & Technology. pp. 261–280.

Muljana, PS, Selco, J, Feldman, R, Gaston, T and **Choi, B.** 2020. When chemical bonding is perceived simple and interesting: The design and development of a learning object. *International Journal of Designs for Learning*, *11*(3), 148–161. DOI: https://doi.org/10.14434/ijdl.v11i3.28801

Nakhleh, MB. 1992. Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education*, *69*(3), 191–196. DOI: https://doi.org/10.1021/ed069p191

Resnick, M. 1998. Technologies for lifelong kindergarten. *Educational Technology Research and Development*, *46*(4), 43–55. DOI: https://doi.org/10.1007/BF02299672

Richey, RC, Klein, JD and **Tracey, MW.** 2011. *The instructional design knowledge base*. New York, NY: Routledge. DOI: https://doi.org/10.4324/9780203840986

Ritzhaupt, AD. 2010. Learning object systems and strategy: A description and discussion. *Interdisciplinary Journal of E-Learning and Learning Objects*, *6*, 217–238. http://www.ijello.org/Volume6/IJELLOv6p217-238Ritzhaupt701.pdf. DOI: https://doi.org/10.28945/1306

Shute, VJ. 2008. Focus on formative feedback. *Review of Educational Research*, *78*(1), 153–189. DOI: https://doi.org/10.3102/0034654307313795

Silva, DR, Hübler, PN, Perry, G, Santos, MB, Carneiro, MLF and **Del Pino, JC.** 2016. Pensaqui: A learning object about chemical transformations. *Journal of Chemical Education*, *93*(2), 387–390. DOI: https://doi.org/10.1021/acs.jchemed.5b00764

South, JB and **Monson, DW.** 2002. A university-wide system for creating, capturing, and delivering learning objects. In: Wiley, DA, (ed.), *The instructional use of learning objects*. Bloomington, IN: Agency for Instructional Technology and Association for Educational Communications & Technology. pp. 223–240.

Sweller, J. 2008. Human cognitive architecture. In: Spector, JM, Merrill, MD, van Merrienboer, J and Driscoll, MP, (eds.), *Handbook of research on educational communications and technology* (3rd ed). New York, NY: Routledge. pp. 369–381.

Sweller, J. 2010. Element interactivity and intrinsic, extraneous, and germane cognitive load. *Educational Psychology Review*, *22*(2), 123–138. DOI: https://doi.org/10.1007/s10648-010-9128-5

Sweller, J, van Merrienboer, JJG and **Paas, FGWC.** 1998. Cognitive architecture and instructional design. *Educational Psychology Review*, *10*(3), 251–296. DOI: https://doi.org/10.1002/ijc.22229

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

Treagust, D, Chittleborough, G and **Mamiala, T.** 2003. The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353–1368. DOI: https://doi.org/10.1080/0950069032000070306

Triona, LM and **Klahr, D.** 2003. Point and click or grab and heft: Comparing the influence of physical and virtual instructional materials on elementary school students' ability to design experiments. *Cognition and Instruction*, *21*(2), 149–173. DOI: https://doi.org/10.1207/S1532690XCI2102_02

Wiley, DA. 2002. Connecting learning objects to instructional design theory: A definition, a metaphor, and a taxonomy. In: Wiley, DA, (ed.), *The instructional use of learning objects*. Bloomington, IN: Agency for Instructional Technology and Association for Educational Communications & Technology. pp. 3–23.

Wolgin, M, Wiedemann, P, Frank, W, Wrbas, K and **Kielbassa, AM.** 2005. Development and evaluation of an endodontic simulation model for dental students. *Journal of Dental Education*, *79*(11), 1363–1372. DOI: https://doi.org/10.1002/j.0022-0337.2015.79.11.tb06034.x

Zamani-Miandashti, N and **Ataei, P.** 2015. College students' perceptions of short message service-supported collaborative learning. *Innovations in Education and Teaching International, 52*(4), 426–436. DOI: https://doi.org/10.1080/14703297.2014.900453

TO CITE THIS ARTICLE:
Muljana, PS and Selco, JI. 2023. Evaluating the Design and Development of the "Making Molecules" Simulation: Students' Perceptions and Recommendations. *Journal of Interactive Media in Education*, 2023(1): 1, pp. 1–16. DOI: https://doi.org/10.5334/jime.772

Submitted: 26 July 2022
Accepted: 16 February 2023
Published: 27 February 2023

Journal of Interactive Media in Education is a peer-reviewed open access journal published by Ubiquity Press.