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Design Tradeoffs of Interactive Visualization Tools for Educational Technologies

Martina Angela Rau, Will Keesler, Ying Zhang, and Sally Wu

***Abstract*—Instruction in most STEM domains uses visuals to illustrate complex problems. During problem solving, students often manipulate and construct visuals. Traditionally, students draw visuals on paper and receive delayed feedback from an instructor. Educational technologies have the advantage that they can provide immediate feedback on students' visuals. This feedback allows students to learn visualization conventions and to learn new content knowledge. This paper presents a design-based research approach to develop visual tools for an educational technology for chemistry. In this research, three design tradeoffs emerged: (1) Which aspects of the drawing task should visual tools constrain? (2) How should visual tools account for variability in students' prior experiences? (3) How should the design of multiple visual tools be aligned so that students can easily transition between them? Our design-based research approach comprises three studies that address each of these design challenges in the context of chemistry visualizations. Our studies yield principles for the design of interactive visual tools for educational technologies.**

***Index Terms*—Educational technologies, visual representations, visualization tools, chemistry.**

I. Introduction

INSTRUCTION in most science, technology, engineering, and math (STEM) domains heavily relies on visual representations [1], [2]. Visuals are external representations that have similarity-based mappings to the constructs they depict [3], [4]. The goal of using visuals in instruction is twofold. First, visuals can help students understand abstract concepts [2]. Second, scientific and professional practices in STEM require that students know how to use visuals for problem solving and communication [4], [5]. To actively engage students in this use of visuals, instruction often asks students to construct visual representations; for example, math students have to draw line graphs of equations, and chemistry students have to draw Lewis structures of molecules. Traditionally, students draw visuals on paper and turn them in to get feedback several days later [6].

Educational technologies offer many advantages over this traditional scenario. They can provide interactive visual tools that allow students to construct visual representations while giving immediate feedback and offering help during the drawing process [6]. Indeed, interactive visual tools are becoming increasingly prevalent in STEM domains. Given that the accessibility of such interactive visuals has increased, calls to use visual tools in STEM instruction have also increased [1].

The development of interactive visual tools for instruction requires attention to different design tradeoffs than the development of visual tools for professionals because (1) mistakes can present opportunities for learning, (2) students may have highly variable prior experiences, and (3) students need to easily transition between multiple visual tools. This paper describes a design-based research project that addressed three design tradeoffs in the context of undergraduate chemistry. Based on three studies, we deduce design principles for instructional visual tools. Because STEM instruction in most domains typically uses multiple visuals for a similar purpose (i.e., to help students understand complex concepts) and via similar activities (i.e., problem solving by constructing and manipulating these visuals), we believe that the instructional design principles that emerge from our research may generalize to other STEM domains. This paper contributes to an existing body of research on learner-centered design and extends this research by providing practical recommendations to resolve design challenges that are specific to instructional visual tools for educational technologies.

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II. Prior Research

A. Learning With Interactive Visual Representations

It is common practice to use multiple visuals in most STEM domains [1]. In fact, educational practice guides emphasize the importance of incorporating multiple visual representations into instruction [1]. According to cognitive learning theories, visual representations can help students learn because they make abstract concepts accessible [3], [7]. Further, different visual representations can provide complementary information [2]. Consequently, students can construct deeper understanding if they can integrate multiple visuals into a coherent mental model of the content [3]. Indeed, there is abundant evidence that visuals can help students learn domain knowledge [2], [4].

In addition, sociocultural theories suggest that visuals are important tools for communication in scientific and professional communities [5], [8]. Indeed, experts often use visuals to reason and communicate about concepts [5]. By participating in such social practices, students learn which visuals are used to explain which concepts. Consequently, instructional activities should help students use of visuals in ways that follow conventions that are common in professional or scientific communities [5].

Both the cognitive and the sociocultural perspective on learning consider the construction of visuals an important part of the learning process [4]. Specifically, students are often asked to draw visuals that depict domain-relevant concepts [9], [10]—an instructional practice that has been shown to enhance students' learning of domain knowledge [11]. Drawing activities are effective because they engage students actively in mapping visual features to domain-relevant concepts and because drawing is an important form of communication in scientific and professional communities [10]. Such activities are common in domains such as biology [12], chemistry [13], math [14], and physics [15]. Yet, for many students, such activities pose an obstacle to learning. In particular, it is well documented that students struggle to draw visuals [16].

Educational technologies can help students overcome these difficulties by providing interactive visual tools that students can construct and manipulate. Based on students' interactions, the educational technology can diagnose students' misinterpretations of visual features [17]. For example, when students use an interactive visual tool to draw, the technology can prompt students to fix mistakes they made in their drawing [6]. Such support has been shown to enhance students' knowledge about the visuals [18] as well as their learning of content knowledge [19]. The goal of this design-based research project is to develop interactive visual tools for educational technologies that help students overcome these difficulties by providing support throughout the drawing process. In the following section, we review design principles for educational technologies that inform the design of our visual tools.

B. *Design of Visual Tools in Educational Technologies*

Similar to visual tools in professional technologies, one design goal for visual tools in educational technologies is that they should be easy to use and allow students to efficiently draw visuals [20], [21]. This goal implies that the difficulty of the drawing task should be reduced, for instance by imposing constraints that allow students to more quickly find options, by automating sequences of routine steps, or by correcting obvious mistakes. To evaluate attainment of this goal, studies often focus on accuracy and efficiency with respect to time and cognitive effort.

In contrast to visual tools for professional use, visual tools in educational technologies have a second goal: to help novice students transition towards expertise [22], [23]. To evaluate attainment of this goal, studies often focus on learning outcomes after completing a task rather than on performance while completing a task [7], [24]. While these two goals do not necessarily conflict, they often yield design tradeoffs.

A first design tradeoff regards the role of mistakes. On the one hand, the efficiency of a visual tool can be enhanced by preventing mistakes students often make when drawing visuals, so as to facilitate efficient and effective drawing [25]. On the other hand, mistakes can provide important opportunities to learn drawing conventions because students can receive corrective feedback [23], [26], [27]. Further, novice students may not know when they need help [28]. Thus, educational technologies should not prevent mistakes that could present learning opportunities but rather provide proactive help that allows students to learn from mistakes [29].

To illustrate this tradeoff with an anecdotal example from our own research, consider students who spend a lot of time making their drawing "look pretty"; they may erase wiggly lines and replace them with straight lines. Spending time on such mistakes is extraneous to the goal of the drawing task, which is to use the visual to understand the content it illustrates. Presumably, a visual tool that automatically constrains drawing actions to straight lines would yield a more efficient learning experience. By contrast, if wiggly lines and straight lines were to communicate key aspects of the target content, then the visual tool should not constrain how the lines are drawn but instead provide feedback that helps the student correct the line. This example illustrates that designers of visual tools for educational technologies face a tradeoff between preventing mistakes by constraining nonessential aspects of the drawing task and allowing for mistakes that present opportunities to learn about domain-relevant concepts and drawing conventions.

A second design tradeoff regards the role of students' prior knowledge and experiences. Both professional and educational technologies should be designed so that they adapt to a varying level of cognitive abilities and prior knowledge of the user [25] and to users' prior experiences [30], which includes their experiences with other types of educational technologies. For educational technologies, this yields an additional complexity because students dramatically differ with respect to their knowledge level and prior experiences [29]. While professional technologies often target users with clearly defined background knowledge (e.g., experts in a given domain), the expressed goal of educational technologies is to support students in their transition from novice to expert. Hence, by definition, their knowledge changes during the interactions with the technology, which yields differing knowledge levels. Further, they may have varying levels of prior experiences from instruction that may or may not have included educational technologies that may or may not have been optimally designed.

To illustrate this tradeoff, consider again an anecdotal example. Because students are introduced to chemistry in middle school and high school, many of them have previously used visual tools. Suppose in their high-school software, students used menu selection to place an atom symbol in a drawing pane, which required three actions: Students (1) clicked a button to bring up a menu, (2) clicked on the atom symbol in the menu, then (3) clicked in the drawing pane to place the atom symbol. An alternative design would ask students to type an atom symbol directly, which requires only two actions: Students (1) click a button to enable a type tool, then (2) type the symbol in the drawing pane. According to keystroke level models of software usability such as GOMS [31], [32], the latter design with fewer actions would be preferable. Yet, students may have prior experience with an educational technology based on the former design with menu-based selection. In this case, they could be confused by the type-based design, even though it is preferable in terms of usability. This example illustrates that designers face a tradeoff between usability considerations for students without prior experience and students who have prior experience with visual tools that are suboptimally designed for the target problems.

A related third design tradeoff applies to the specific case of educational technologies that involve multiple interactive visual tools. On the one hand, the tools should be designed so that students' prior experiences with one tool transfer to the other tool [33], [34]. The more similar the look and functionality of tool components are, the more likely students may be to transfer their skills from one to the other [9]. On the other hand, each tool should be designed in a way that facilitates efficient and effective problem solving and communication among members of the target scientific or professional community [25]. If usability design considerations for each tool do not align across tools, transfer across tools may be reduced, which could in turn reduce usability and learning. Consequently, designers face a tradeoff between alignment considerations across multiple visual tools and usability considerations for each individual visual tool.

TABLE I
OVERVIEW OF DESIGN TRADEOFFS

Tradeoff	General usability considerations	Usability considerations specific to educational technologies
1	Preventing mistakes by nonessential aspects of the drawing task	Allowing for mistakes that presen learning opportunities
2	Enhance usability for students without prior experiences	Meeting expectations of students who have prior experience with suboptimally designed visual tool
3	Enhance usability of each visual tool	Align design across multiple visual tools

Table I summarizes these three design tradeoffs. The goal of our research is to develop instructional design principles for visual tools that address these tradeoffs. We chose undergraduate chemistry as a context to address this goal for two reasons. First, like many other STEM domains, chemistry instruction heavily relies on multiple visual representations [35]. Second, even though many educational technologies involve multiple interactive visuals (for an overview, see [36]), they typically do not offer adaptive support for students to draw visuals. For example, many interactive tools to construct visuals provide no guidance as to how to do so [37]–[39]. Other tools provide error-specific feedback on problem solving, but not on students' interactions with visuals [13], [40]–[42]. Our development of interactive visual tools addresses this shortcoming.

III. Research Questions

In developing visual tools for chemical molecules, we encountered the three design tradeoffs just described. To resolve these tradeoffs, we followed a design-based approach [43], [44] that involved comparing experts and novices, iterative development based on user studies with the target population, and an evaluation study. Taken together, the overarching question of this project was: what are tradeoffs usability considerations concerning ease of use versus educational goals? We considered the following three tradeoffs:

1) Mistakes that can be constrained because they are nonessential *versus* mistakes that should be allowed because they present learning opportunities
2) Ease of use for students with varying levels of prior experiences with drawing tools
3) Ease of use of individual drawing tools *versus* ease of transitioning across multiple visual tools

The three studies that were part of this design-based research project each addressed one tradeoff. Based on these studies, we deduced general principles for the design of visual tools.

IV. Study 1: When to Prevent vs Allow Mistakes?

In Study 1, we investigated design tradeoffs between mistakes that can be constrained because they are nonessential versus mistakes that should be allowed because they present learning opportunities. To this end, we conducted an empirical cognitive task analysis that compared what expert chemists consider as essential or nonessential in drawing Lewis structures, arguably the most prevalent visual representation in chemistry. We compared the expert data to mistakes undergraduate chemistry students make when drawing Lewis structures to determine which mistakes are nonessential or offer learning opportunities.

A. Experts

Our first step was to investigate how expert chemists draw Lewis structures, and which aspects they view as essential for following established disciplinary conventions for communication and for illustrating key chemistry concepts.

1) Methods: Materials. To create materials for the expert cognitive task analysis, we reviewed instructions on how to draw Lewis structures to show concepts related to covalent bonding in chemistry textbooks (e.g., [45], [46]). This allowed us to identify concepts that Lewis structures communicate in instructional materials. Based on this review, we compiled nine molecules that frequently appeared in the reviewed instructional resources and that communicated the identified key concepts.

Participants. We recruited five chemistry experts via email to participate in a 30-minute session. They were graduate students with over five years of experience in drawing Lewis structures to reason about the identified concepts and were hence considered experts in drawing Lewis structures of the selected molecules. They received $10 for their participation.

Materials. Experts were asked to draw Lewis structures of the nine molecules on separate blank pages. Molecule names were provided with the chemical formula. They were given a pencil and permission to erase or cross out their drawings. They had access to a periodic table, which was printed on paper and turned upside down so that we could see when they used it.

Procedure. Sessions were conducted individually with each expert. Experts were asked to think aloud while drawing the Lewis structures [47]. The interviewer did not interrupt the drawing process but took notes on corrective behaviors (e.g., if the expert commented on having to correct something or erased part of the drawing) and visual features that the expert seemed to pay particular attention to (e.g., if the expert mentioned taking care of drawing a feature accurately or slowed down to draw a feature accurately). After each drawing, a semi-structured interview served to ask the experts to explain what their drawing showed and why they drew it the way they did. The interviewer used the notes to ask follow-up questions about aspects the expert did not mention spontaneously. Sessions were videotaped and transcribed.

Analysis. To identify which aspects of Lewis structures expert chemists view as essential, we used a grounded theory approach [48], [49]. Specifically, we reviewed the transcripts, noting all visual features the experts mentioned in the interview. Next, we formalized these features as codes, which were then applied to the transcripts by the primary coder. 25% of the transcripts were coded separately by another coder to establish interrater reliability. Interrater reliability was high with Cohen's kappa = .92. Finally, we identified visual features and concepts that were mentioned by at least three experts as essential aspects of the drawing task.

2) Results: Fig. 1 illustrates several essential aspects of the drawing task. One conventional aspect was the capitalization of the first letter of atom symbols (Fig. 1a). A conceptual aspect of Lewis structure drawings regards the placement of dots that show electrons. Experts took care to indicate which atom dots "belonged" to by placing them close to that atom, allowing them to check if the Lewis structure fulfills the octet rule (Fig. 1b). Further, they ensured that it correctly follows the convention of paired electrons being placed close together (Fig. 1c). Another conceptual aspect was the number of lines that indicate bond order; that is, whether a bond is a single, double, or triple bond (Fig. 1d).

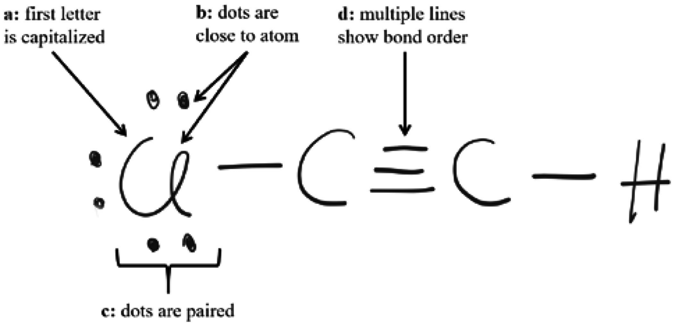


Fig. 1. Annotated drawing of chemical molecule. Letters show atoms, lines show bonds, dots show electrons. a: the first letter is capitalized. b: Dots are placed close to the atom to which they belong. c: Paired electrons are placed close together. d: Multiple lines indicate higher-order bonds.

B. Novices

Our second step was to investigate how novice chemistry students draw Lewis structures and what mistakes they make.

1) Methods: Participants. Ten novice chemistry students were recruited from a first-semester introductory chemistry course via flyers for a 30-minute session. The study took place before students in this course received formal instruction on Lewis structures.

Materials, procedure, and analysis were identical to the expert study. Interrater reliability was determined on 10% of the transcripts and was high with Cohen's kappa = .95.

2) Results: The think-alouds during the drawing task allowed us to identify several difficulties in drawing Lewis structures. First, seven students expressed difficulties in determining how many dots the Lewis structures should show for electrons. While all students consulted the periodic table to determine the number of electrons of an atom, these students did not know how to use this information when drawing Lewis structures of molecules. Second, eight students had difficulties determining bond order. Among them, six students erased parts of at least one of their drawings to make changes. During the think-alouds, these students also expressed being unsure about bond order. In the interviews, these students clarified that they were unsure about the number of electrons and bond order in their drawings, hence corroborating the finding that these aspects are difficult for students. Finally, eight students mentioned making decisions for how to draw the Lewis structures based on aesthetic considerations.

Our analysis of the drawings themselves revealed several common mistakes: (a) they contained incorrect atom symbols (i.e., an atom symbol that does not exist or the correct atom symbol without capitalizing the first letter), (b) bond order was incorrect (e.g., a single bond was depicted as a double bond), (c) the number of electrons was incorrect (i.e., missing electrons or too many electrons), or (d) electrons were paired incorrectly (i.e., the right number of electrons was shown but the drawing did not clearly indicate which electrons were paired). No other mistakes were identified. This metric revealed that the average number of mistakes per drawing was 2.96 (i.e., across the 90 generated drawings generated by 10 students, there were 267 mistakes). The average number of mistakes per student were 6.68 mistakes across the nine drawings.

C. Discussion

Comparing experts and novices allowed us to distinguish mistakes that should be prevented because they are nonessential aspects of the drawing tasks and mistakes that are should be allowed because they present essential learning opportunities. We note that we selected novices who were enrolled in a chemistry course because we consider them the target population of our visual tools. It is possible that our results do not generalize to students who are not interested in learning chemistry, or to more advanced chemistry students.

We identified two mistakes that provide opportunities to learn disciplinary drawing conventions. First, mistakes such as drawing incorrect atom symbols can allow students to learn to draw correct atom symbols. This mistake yields learning opportunities if the tool provides help and feedback to identify correct atom symbols, misspell the symbol, or draw the wrong number of atoms. Second, mistakes in electron pairings can allow students to learn to depict electrons as paired or unpaired. This can create a learning opportunity for the tool to provide corrective feedback if students show incorrect pairings.

Third, we identified one type of mistake that presents an opportunity for conceptual learning about electrons. The visual tool should allow students to draw an incorrect number of electrons so they can learn to identify the correct number of electrons. Further, our data indicates that students need help in using the periodic table to find an atom's number of electrons. Hence, allowing for this mistake may enhance learning if the tool directs students to relevant parts of the periodic table when they request help and when they receive corrective feedback.

Fourth, we identified a mistake that presents an opportunity for conceptual learning about bond order. Specifically, the visual tool should allow students to draw incorrect bond orders. This can create a learning opportunity if the tool gives help and feedback that instructs students on how to use information about the atoms to determine bond order. Further, the tool should make it easy to modify the bond order, which aligns with our finding that students often changed bond order in their drawings by erasing and redrawing bonds.

In addition, the expert-novice comparison revealed nonessential mistakes that can be constrained. These are aspects of the drawing task that novice students spent time on even though experts did not view as important. A prominent example was that novices spent time arranging the atom symbols based on aesthetic considerations, whereas experts did not. The visual tool can constrain aesthetic aspects of drawings so that electrons are at a uniform distance from the atom, or by making atom symbols and electrons of uniform size and lines to be straight.

In sum, by comparing experts and novices, we identified tradeoffs between nonessential mistakes that should be prevented and essential mistakes that should be allowed (research question 1). Our analysis suggests that mistakes should be allowed if they present opportunities to learn drawing conventions that students do not intuit, to integrate information from multiple resources that students find difficult to navigate, and to practice applying conceptual knowledge in problem solving. Furthermore, our analysis suggests that prevalent time-consuming nonessential behaviors often involve drawing aesthetics. This suggests that a promise of visual tools is to enhance the efficiency of drawing activities by automatically rendering them in ways that align with students' preferences.

V. Study 2: Accounting for Prior Experiences

Based on Study 1, we developed an initial version of a Lewis structure tool. The goal of Study 2 was to explore design tradeoffs

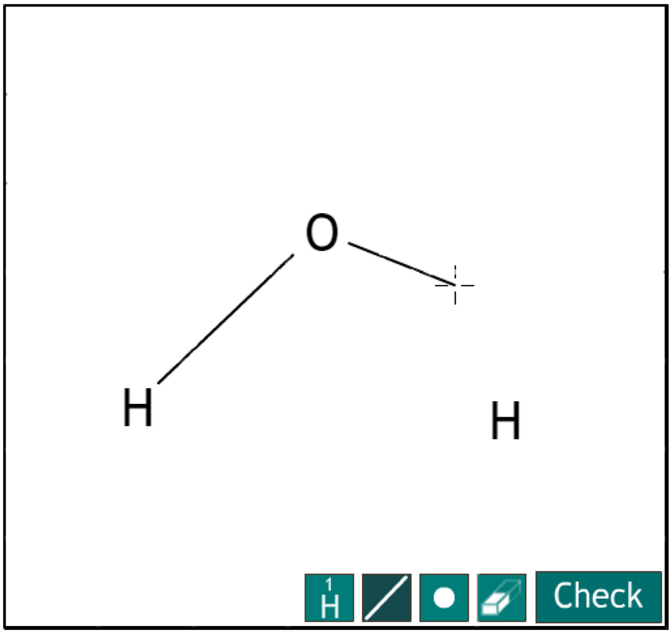


Fig. 2. Round 1 of pilot-testing with the Lewis structure visual tool. In the initial version, students type atom symbols and click to add bonds and electrons. An eraser tool deletes atoms and bonds.

regarding the ease of use for students with varying levels of prior experiences with drawing tools. To address this question, we conducted four rounds of user testing and redesign with undergraduate chemistry students.

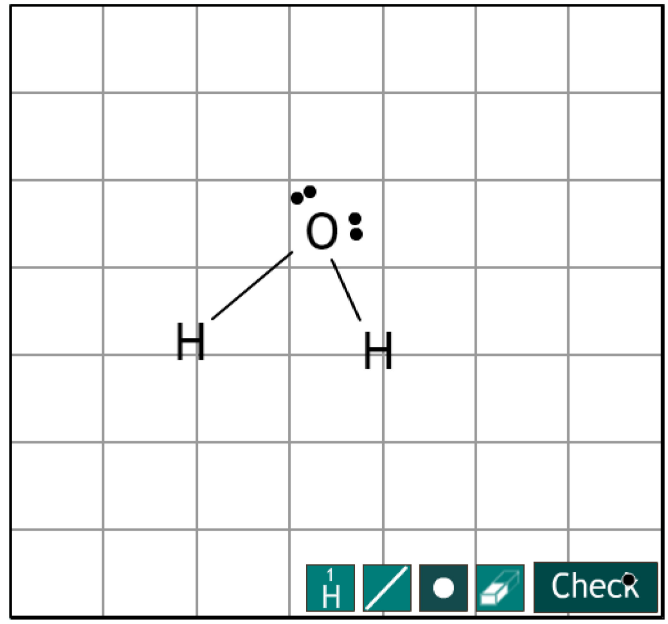
A. Methods

1) Participants: Altogether, 20 undergraduate freshmen students were recruited via flyers from introductory undergraduate chemistry courses. Eighteen students had taken chemistry in high school. Twelve had prior experience in using visual tools to show chemistry concepts from high school.

2) Materials: We conducted four rounds of user testing, each with an updated version of the Lewis structure tool (Fig. 2-5) based on findings from the prior round. In each round, students were asked to draw the nine molecules from Study 1.

3) Procedure: User tests were conducted individually with each student. Students were asked to draw a series of nine molecules while thinking aloud. The interviewer provided no help. He took notes of aspects the student seemed to struggle with. Then, he showed the visual tool and asked for comments about the tool. The interviewer used his notes to ask specific questions about each of the components. Sessions were audiotaped and transcribed.

4) Analysis: To identify tradeoffs between usability considerations for students with or without prior experiences with visual tools, we used the following qualitative approach. First, we examined the transcripts for usability issues related to confusion about how to operate the tool, difficulties while drawing, and preferences. Second, we examined each case for whether the usability issue seemed to stem from prior experiences with other visual tools or not. Third, for each case, we examined student suggestions. Fourth, for each case, the research team discussed how to change the visual tool for the next round. A new round was started when the team reached a consensus that new suggestions repeated those we planned to address in the next version.



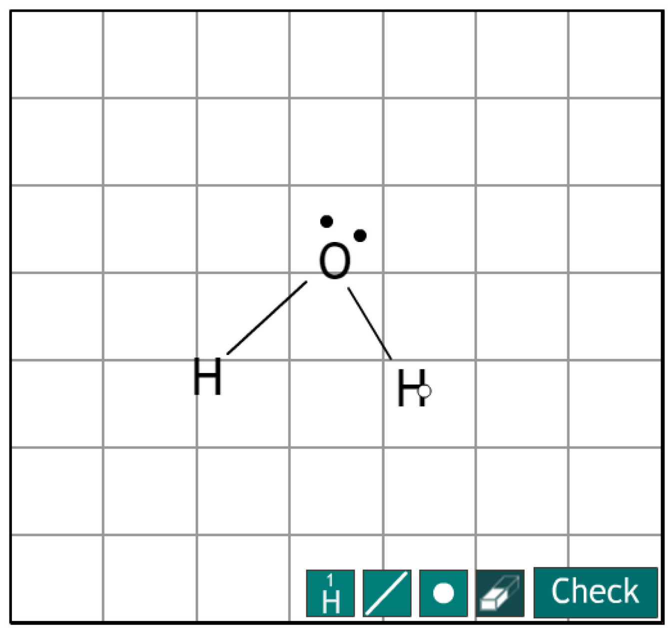


Fig. 3. Round 2 of pilot-testing with the Lewis structure visual tool. Top: electrons are automatically paired. Bottom: students click on the atom they want to erase.

B. Results

1) Round 1: Three students who had prior experiences with various other visual tools participated in this round of user testing.

Description of visual tool. In round 1 (see Fig. 2), the Lewis structure tool did not provide feedback. Students were given an empty drawing pane. To add atom symbols, they clicked on a button to activate a typing tool and then clicked in the pane to place a text box to type the atom symbol. To draw bonds, they clicked on an atom and dragged a line to a second atom. To add electrons, they activated a dot tool and clicked on the atom to add dots, which snapped into place around the atom. To erase, students

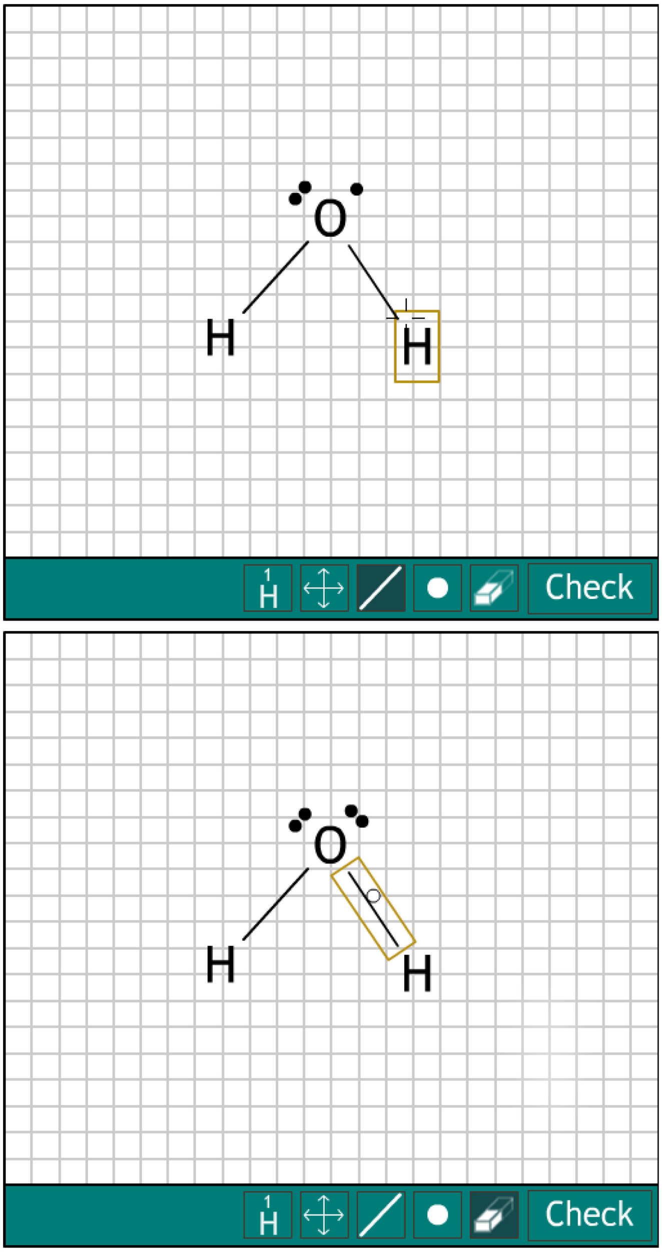


Fig. 4. Round 3 of pilot-testing with the Lewis structure visual tool. Top: when placing bonds, the atom the bond attaches to is highlighted. Bottom: the eraser tool highlights what it deletes.

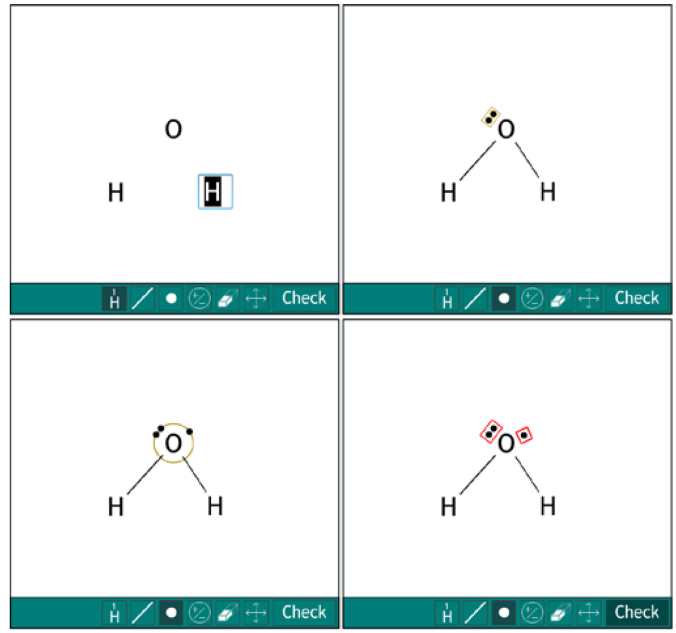


Fig. 5. Round 4 of pilot-testing with the Lewis structure tool. Top left: when students add atoms, the tool populates the text box with the previous atom symbol. Top right: when students place electrons, the tool highlights which electrons are paired. Bottom left: when students place electrons, the tool highlights which atom they attach to. Bottom right: when students make a mistake, highlights show incorrect parts of the Lewis structure.

activated an eraser tool and clicked on the instance they wanted to erase. Students did not have to pair electrons.

Student responses. We noted several usability issues that emerged across students. One usability issue seemed to result from prior experiences. All students were confused about how to start drawing. This confusion stemmed from prior tools having students place atoms by clicking on a button that opens a menu of different atom symbols. Given these experiences, students expected a menu to pop up when they clicked on the atoms symbol. When that did not happen, they thought they could only place hydrogen atoms because that is the atom symbol the button showed. However, once they clicked in the drawing pane, they realized that they could type any atom symbol and were no longer confused about this function.

Several usability issues related to essential mistakes that, as per Study 1, we chose not to constrain. First, all students had trouble adding bonds and electrons, often clicking without effect. They said they did not know how to get bonds or electrons to "stick" to an atom and would like to some feedback on this. Second, two students commented on feedback, expressing a desire for more detailed feedback on what is wrong. One student suggested that it would be helpful to highlight the incorrect part of the Lewis structure. Third, one student suggested to automatically capitalize atomic symbols.

Further, several usability issues related to nonessential mistakes that, as per Study 1, we chose to constrain. These issues related to functionalities that would make Lewis structures "look prettier." One student suggested a grid would help align atom symbols and bonds. Another student suggested a move function to rearrange atoms and bonds.

Finally, we examined general usability aspects of the tool. We identified one issue: all students were confused about the eraser function. When activating the eraser, they did not know what it would delete because it did not indicate which atoms or bonds it attended to when hovering over them. We also found that students generally liked the visual tool: they commented on the ease of drawing that placing atoms and bonds was intuitive, and that the process was similar to drawing on paper.

Discussion. The usability issue most relevant to research question 2 relates to the typing function. Students with prior experiences expected to select atom symbols from a menu, which contrasted with our implementation of typing the atom symbol. One reason for this choice is that typing provides opportunities to learn atom symbols, which is one of the essential aspects of the drawing task identified in Study 1. Interestingly, this choice also seemed to conflict with one student's suggestion to automatically capitalize the first letter of atom symbols. To address this tradeoff, we added more detailed instructions on how to use the tool, and added feedback that explained that students had to capitalize atom symbols if they did not. Further, we added feedback to a variety of other types of mistakes that we had decided to allow based on Study 1. In addition, we made several changes to the tool to address usability issues related to mistakes we had decided to constrain based on Study 1. We added grid lines to make it easier for students to draw visually appealing Lewis structures. We also designed the bond and electron functions to communicate more clearly when they would attach to a given atom. Further, we identified general usability issues of the eraser tool. We made modifications to communicate what it would erase.

2) Round 2: Three students participated in this round of pilot testing. All of them had prior experience with other visual tools. None of them had participated in round 1.

Description of visual tool. To address the issues identified in round 1 regarding prior expectations for the atom symbol tool, we changed instruction to say that students need to "type" the atom symbol rather than to "add" the symbol. Further, we added hints that provided step-by-step instructions for drawing a correct Lewis structure. Related to this issue as well as to essential mistakes, we implemented corrective feedback when students (a) drew an incorrect number of atoms, (b) misspelled atoms, (c) drew an incorrect number of bonds, (d) drew an incorrect number of electrons, or (e) did not pair electrons. Further, to address nonessential mistakes, we added grid lines in the background of the drawing pane as shown in Fig. 3. Finally, to address general usability issues, we added a pairing function for electrons so that electrons stuck to each other at a fixed distance to indicate pairing (see Fig. 3, top).

Student responses. With respect to usability issues that seemed to result from prior experiences, three students commented on the typing function of the atom symbol tool. One student said she liked typing the atom symbols, even though it conflicted with her prior experiences with another drawing tool. She said she immediately figured out how to place atoms because the text boxes made it obvious that one had to type the atom symbols. Another student said that this tool was much easier to use than another tool she had experience with. Yet, one student said she did not know that one had to capitalize atom symbols. With respect to usability issues related to essential mistakes, students commented on the feedback being useful. One student said it helped her distinguish paired and unpaired electrons. About usability issues for nonessential mistakes, several students commented on the grid. Two students said they found it distracting. Another student suggested that the grid is too large. Further, one student suggested that a move function would be helpful, which parallels comments from round 1. With respect to general usability, feedback was largely positive: students commented on the ease of drawing atoms and bonds. Yet, we also identified a usability issue related to the bond tool: two students mentioned that bonds sometimes did not stick to atoms, and two students mentioned that the eraser tool did not indicate what it would erase (see Fig. 3, bottom). With respect to the latter, students suggested to highlight what it would erase.

Discussion. The instructions and feedback on the typing function of the atom symbol tool seemed to allow students to cope with the functionality of having to type atom symbols even if it conflicted with their expectations. Students' comments suggest that having to type the symbols allowed them to learn that they had to capitalize atom symbols if they did not already know to do so. With respect to essential mistakes, students' comments were in line with our expectation that they would find feedback helpful. With respect to nonessential mistakes, the grid did not seem to help students. To address this issue, we redesigned the grid. Further, in response to students' suggestions, we added a move tool. Finally, we identified general usability issues that we sought to address through modifications to the bond and eraser tools.

3) Round 3: Six students participated in this round of user testing. Three of them had prior experiences with other visual tools. None of them had participated in rounds 1 or 2.

Description of visual tool. To address issues regarding nonessential mistakes, we reduced the size of the grid (see Fig. 4). We added a move tool so that students could rearrange the placement of atoms and electrons. Further, to address general usability issues, a highlighting function was added to the bond tool so that a rectangular highlight would appear around the atoms that students connected by bonds (see Fig. 4, top). As illustrated in Fig. 4 (bottom), highlighting was also added to the eraser tool so that it showed a rectangular highlight around the atom, bond, or electron it would erase. The electron tool was modified so that the electrons stuck to the outside of the atom to indicate where they would be placed. Finally, we made some aesthetic improvements to the layout of the button icons.

Student responses. Regarding prior experiences, the typing function of the atom symbols tool again received multiple comments from students. Three students said that it was cumbersome to repeatedly type the same atoms. These students had experience with a drawing tool that used menu-based selection of atom symbols, which would allow them to repeat the activated atom. Two of these students suggested to autopopulate the typing function with the previous atom. Another student suggested a copy-and-paste function. With respect to essential mistakes, four students said they liked the hints and feedback. However, we identified an issue regarding the electron function: all students had trouble pairing electrons because the tool did not indicate when it recognized pairings. Students were frustrated if they thought they had paired electrons but received feedback that they had not. With respect to nonessential mistakes, three students disliked the grid; they tried to ignore it or but found it distracting. Four students liked the move function. However, they said they expected to also be able to move electrons. With respect to general usability, all students said they liked the tool, that it was intuitive, and aligned with their courses. Further, highlighting of the eraser tool seemed to clearly communicate what it would delete. Yet, one student was frustrated that the eraser deleted multiple bonds (e.g., it would delete an entire triple bond instead of reducing it to a double bond).

Discussion. With respect to prior experiences with menu-based selection of atom symbols, we found that menu-based selection had the unanticipated advantage of making it less cumbersome to add multiple atoms in a row. To address this issue, we added an autopopulating function. With respect to essential mistakes, we found that the tool needs to indicate whether electrons are paired. With respect to nonessential mistakes, we found that the move tool was helpful, whereas even the modified version of the grid was not. Hence, we expanded the move function to electrons and excluded the grid. Finally, we found remaining usability issues for the eraser tool.

4) Round 4: Seven students participated in this round of user testing. Four of them had prior experiences with other visual tools. None of them had participated in rounds 1-3.

Description of visual tool. To address issues regarding students' prior expectations for the atom symbols tool, we added an autopopulating function so that the previously typed atom would appear in the text box the student placed next (see Fig. 5, top left). To address issues regarding essential mistakes, highlighting was added to the electron pairing function, such that a rectangular highlight would indicate that electrons were paired (see Fig. 5, top right). Highlighting was added to the electrons function so that a round highlight would appear around the atom to which the electrons belonged (see Fig. 5, bottom left). We also added a highlighting function for feedback so that a red rectangular highlight would appear around the component students had drawn incorrectly (e.g., the electrons; see Fig. 5, bottom right). To address issues regarding nonessential mistakes, we removed the grid. Finally, we modified the eraser tool so that it erased only one bond at a time.

Student responses. With respect to prior experiences with menu-based selection of atom symbols, we found that students liked the autopopulating function. Four students said the fact that the given text was highlighted communicated that they could change it. With respect general usability issues with the eraser tool, six students said that they liked the highlighting that communicated what would be erased, which atoms electrons and bonds would attach to, and which electrons were paired.

Discussion. Students' responses to this version of the Lewis structure tool were overwhelmingly positive. They suggest that the remaining issues resulting from prior experiences and regarding nonessential mistakes were resolved. Further, we discovered no new usability issues.

C. Discussion

Study 2 identified design tradeoffs regarding the ease of use for students with varying levels of prior experiences with a variety of drawing tools. We note that while we believe that the range of prior experiences was representative for students in our target population for our university, the fact that we sampled from only one university suggests that our results may not generalize to the broader population of undergraduates.

We found that many students had prior experiences that led them to expect that they could add atoms by selecting atom symbols from a menu. Based on prior usability considerations, we had instead designed the visual tool so that students could type the symbols. Study 2 showed that the typing function also had the advantage to allow students to learn from one of the mistakes we had identified as essential in Study 1, namely the mistake of not capitalizing the first letter of an atom symbol. Yet, we also identified an unanticipated disadvantage of the typing functionality: students found it cumbersome to repeatedly type frequent atom symbols—especially if they had prior experiences with other tools that used a menu-based approach, which naturally allows to repeat atom symbols. To address these design tradeoffs, we added an autopopulating function to the atom symbol tool that automatically added the previously typed atom in the text box while using highlighting to indicate that students could change the text. Further, we added subtle instructions in the form of text and on-demand hints that addressed students' potential prior expectations. We found that these design choices resolved the tradeoff so that students quickly got used to this functionality and appreciated its ease. In addition, we identified that several general usability issues, such as communicating which atom a bond would stick to, impeded our goal to allow for learning from essential mistakes and to prevent nonessential mistakes.

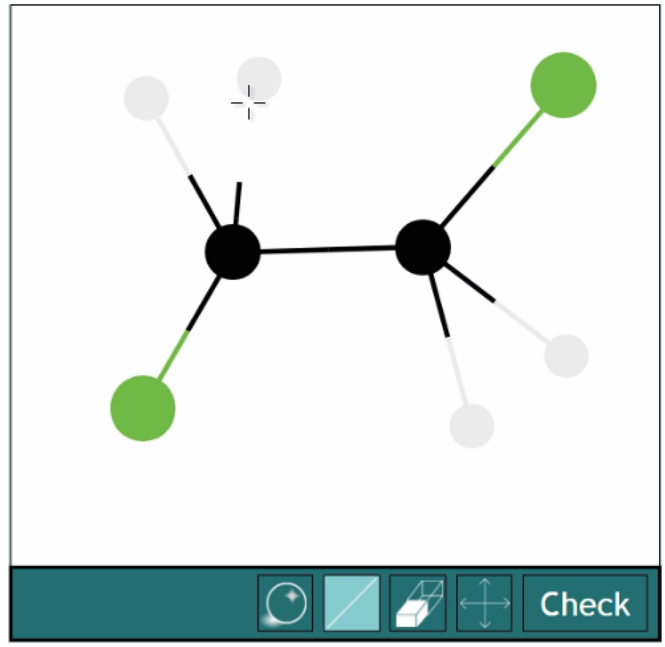


Fig. 6. Interactive ball-and-stick visual tool. Students place atom spheres in the drawing pane and draw bonds between the atoms.

In sum, this study shows that design tradeoffs that result from prior experiences should be considered in conjunction with functionalities that allow students' to learn from essential mistakes and functionalities that prevent nonessential mistakes. Instructional designers should examine whether students' prior experiences yield expectations of functionalities that are useful and could be incorporated in the design of the tool without compromising other usability considerations related to essential and nonessential mistakes. Further, simple tweaks to instructions on the functionalities of the visual tools may suffice to communicate that the functionality may differ from competing expectations that result from prior experiences.

VI. Study 3: Designing for Transitions Between Tools

Studies 1 and 2 focused on one particular visual representation: Lewis structures. The goal of Study 3 was to investigate design tradeoffs between the ease of use of individual drawing tools versus the ease of transitioning across multiple visual tools. To this end, we developed a second interactive visual tool for ball-and-stick models, which are also commonly used in chemistry instruction. We used the results from Studies 1 and 2 to inform the design of an interactive ball-and-stick model tool. In doing so, our goal was to facilitate transitions between the visual tools by aligning the design and functionality of the ball-and-stick model tool with the Lewis structure tool. In the following, we describe a series of studies that address tradeoffs between alignment considerations and usability considerations.

A. Pilot Study: Button Design Tradeoff

Ball-and-stick models show atoms as colored spheres, using a color code to denote atom identity. Bonds are shown as lines, electrons are not shown. Fig. 6 shows the ball-and-stick tool.

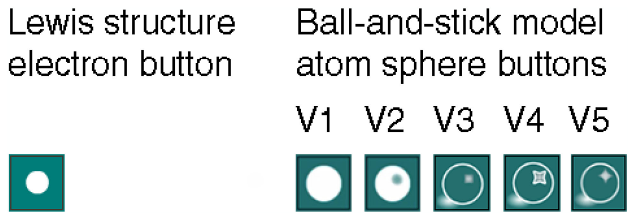


Fig. 7. The initial version of ball-and-stick model button for atom spheres (right, V1) resembled the Lewis-structure button for electrons (left). V2-V5 show versions of the redesigned buttons; V5 is the final version.

1) Methods: Participants. Five students participated in this pilot study. Because our goal was to align the design of the ball-and-stick tool with the Lewis structure tool, we recruited students who had previously used the final version of the Lewis structure visual tool described in Study 2. Because our goal was to evaluate the usability of the tool rather than its instructional effectiveness, students had extensive experience in drawing Lewis structures and with the molecules we asked them to draw.

Materials. We conducted five rounds of pilot-testing, each with an updated version of the ball-and-stick model tool based on our findings from the previous round. In each round, students were asked to draw six common molecules.

Procedure and analysis methods were identical to Study 2, except that students worked with the ball-and-stick model tool.

2) Results: Version 1. The pilot-tests revealed a design tradeoff regarding the button students clicked to place atom spheres. Fig. 7 (right) shows different versions of this button. The initial version of the ball-and-stick tool used the “V1” button in Fig. 7. All students thought it would add electrons and were hence confused about which button to click to place atoms. In the interviews, they said that the atoms button looked very similar to the electrons button in the Lewis structure (Fig. 7, left).

Version 2. We redesigned the button to look less similar to the electrons button in the Lewis structure by adding a reflection in the center of the sphere (“V2” in Fig. 7). We pilot-tested this version with the same students. They still found it too similar to the Lewis structure button. In addition, one student said the button looked like the “death star” in Star Wars.

Version 3. We redesigned the button as shown in “V3” in Fig. 7, using a white outline instead of a solid white sphere and adding a shadow to the sphere. We pilot-tested this version with the same students. Results showed that students no longer felt the button looked too similar to the Lewis structure electrons button. However, they suggested making the reflection larger.

Version 4. We redesigned the button as shown in “V4” in Fig. 7, with an outline around the reflection. Most students liked the button and had no further comments, but two students thought the outline was odd and distracted from the shape of the sphere.

Version 5. We redesigned the button as shown in “V5” in Fig. 7. Pilot-testing showed no further need for modifications. Hence, this button was used in the final version.

3) Discussion: The pilot study identified a design tradeoff that results from visual similarities. We note that we purposefully recruited students who had experience with our Lewis structure tool. Hence, our results do not necessarily generalize to transitioning from any Lewis structure tool to the ball-and-stick model tool. Our results showed that visual similarities in the design of buttons was misleading because they were associated with different functionalities. Hence, instructional designers should carefully compare visual tools to identify visual similarities that are informative in the sense that they communicate similar functionalities and visual similarities that are incidental in the sense that they are associated with different functionalities.

B. User Study: Menu-Based Selection of Atom Spheres

As per Study 2, the Lewis structure tool uses a typing function to place atoms. Yet, because the ball-and-stick model shows atoms as colored spheres, it requires menu-based selection. This difference might cause confusion and impede students’ transition from Lewis structures to ball-and-stick models. To investigate this design tradeoff, we conducted a user study with students from the target population.

1) Methods: Participants. Five undergraduate freshmen were recruited via flyers from the same chemistry course as Study 2. All had taken chemistry in high school and had prior experience with visual tools. None had participated in the pilot study.

Materials. To mimic a situation in which students realistically use the visual components, we created an instructional sequence that first provided a short video introduction into how to use the Lewis structure tool. Then, students received three Lewis structure problems that contained instructional information on how to draw molecules. Then, students received a short video introduction into how to use the ball-and-stick tool. We were interested in their interactions with five following problems that asked students to draw ball-and-stick models of common molecules without additional instruction. We chose to present ball-and-stick models after Lewis structures because this sequence matches the sequence in which these representations are typically used in chemistry curricula used in the courses we designed these tools for. Students had access to hints, the code for sphere colors, and a periodic table. Further, students received error feedback if they submitted an incorrect ball-and-stick model.

Procedure and analysis was identical to Study 2, except that students worked on an instructional sequence of Lewis structure and ball-and-stick model problems.

2) Results: To address research question 2, we focused primarily on students’ ability to transition from the Lewis structure to the ball-and-stick model, in particular on whether differences in the functions to place atoms posed a problem for students (i.e., typing in the Lewis structure tool versus menu-based selection in the ball-and-stick tool). No student seemed to have an issue with these differences. One student commented directly on this difference, mentioning that transferring was easy because “they were really similar which was helpful.” Students noticed the difference: “Like the buttons were mostly the same except for when, like, the different, you had to type it in rather than use the ball.” However, the difference seemed intuitive because of the different nature of the representations: “But they had to be different since it was like a different diagram.” Further, students found working with the ball-and-stick tool easier than working with the Lewis structure tool. For two students, this preference was due to the colorful balls being more aesthetically pleasing than the letters and because they showed atomic radii: “I, uh, the second tool I liked better. The colors really did it for me.” The other students did not give a reason for their preference, but we note that the molecules they had to draw with the ball-and-stick model were more complex than those they had to draw with the Lewis structure. Also, drawing ball-and-stick models is more difficult in general because they do not explicitly show electrons and hence make it less salient whether atoms satisfy the octet rule. Hence, we think students finding the ball-and-stick model as easier is not due to the task being easier but may be attributed to their experience with the Lewis structure helping them draw ball-and-stick models. In sum, it seems that the differences in functions for atom placement did not pose an obstacle to students' ability to transition between the tools.

In addition, we noted several general usability issues. All students recommended adding more instruction to the ball-and-stick model problems. Four students felt that hints alone were subtle and asked for step-by-step instructions as in the Lewis structure problems. All students said they found the tool aesthetically pleasing, liked its simplicity, and found the hints helpful. All emphasized they appreciated receiving feedback and felt that this tool would be a good addition to current activities in their courses where they receive feedback on paper-based drawings by their teaching assistants a week later. Finally, three students said that the Lewis structure and the ball-and-stick tools matched the content taught in their courses.

3) Discussion: Again, we note that our sampling procedure implies that our findings may be specific to our Lewis structure and ball-and-stick model tools. The user tests did not reveal a design tradeoff due to different functionalities of atom placing between the tools. We attribute this finding to the fact that—even though students engage in corresponding actions of placing atoms in both tools—the button design for these actions is sufficiently dissimilar so that students do not expect similar functionalities and are hence not confused that the Lewis structure tool uses a typing function whereas the ball-and-stick model tool uses a menu-based function. Next, we examined if this holds in a realistic context.

C. Classroom Study: Embedding Visual Tools in Instruction

To further investigate whether students can easily transition between the Lewis structure and ball-and-stick model tool, we conducted an observational study with students who used these tools embedded in an instructional sequence. We examined whether students' proficiency in drawing visuals improves while they use the visual tools, in particular when they transition between tools. We also explored whether their use of the tools was associated with learning of chemistry content.

1) Methods: Participants. 85 undergraduate students participated. They were recruited via flyers from introductory undergraduate chemistry courses. They were paid for their participation.

Materials. Students worked with an educational technology, Chem Tutor [50], which included the Lewis structure and ball-and-stick model tools. The visual tools were embedded in instructional problems that served to practice chemistry content covered in the chemistry course. We focused on two weeks in which students used Lewis structures in six problems (CH_4, CO_2, NH_3, C_2H_6, H_2O, and C_2S) and on one subsequent week in which students used ball-and-stick models for two problems ($C_2H_4Cl_2$ and C_2H_2). The Lewis structure weeks focused specifically on practicing how to draw Lewis structures, whereas the ball-and-stick model week focused on chemistry content illustrated by ball-and-stick models. Hence, the fact that students received more practice opportunities with Lewis structures reflects common practices of using these visuals in general chemistry instruction.

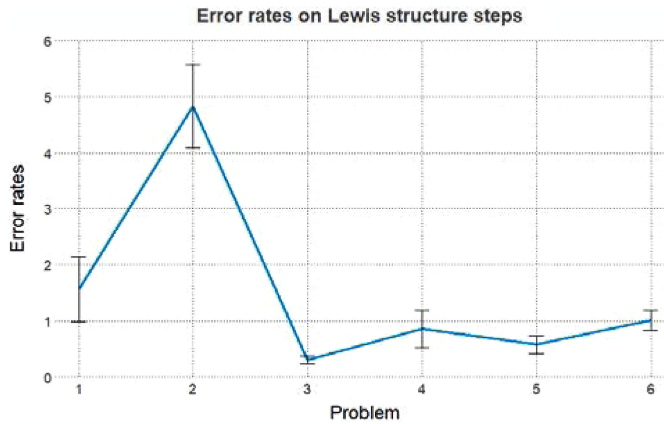


Fig. 8. Error rates across problems in which students draw Lewis structures. The y-axis shows the number of errors in drawing a correct Lewis structure in each problem. The x-axis shows the sequence of problems with Lewis structures. A decrease in error rates indicates that students became more proficient at drawing Lewis structures.

Procedure. Students worked with Chem Tutor over 11 weeks once a week in a classroom dedicated to this study. Each week, students received a pretest and a posttest to assess their knowledge of the content covered in the given week. One week later, they received a delayed posttest.

Analysis. We used Chem Tutor logs to analyze error rates while students used the visual tools to draw Lewis structures and ball-and-stick models. As an indicator of increased proficiency in drawing the visuals, we consider decreased error rates across problems that use these visuals. Further, we used test data to assess students' learning of chemistry content.

2) Results: Proficiency in drawing visuals. Our main goal was to investigate students' ability to transition between the visual tools. A first step in this analysis was to verify whether students became more proficient at drawing visuals over the course of their interactions with these tools in Chem Tutor. Hence, we first tested whether students' error rates decreased across problems that asked them to draw Lewis structures. To this end, we conducted a repeated measures ANOVA with the six Lewis structure problems as repeated factor and the number of errors made per problem in drawing a Lewis structure as dependent variables. Results showed a large significant effect of problems, $F(5, 84) = 16.23$, $p < .001$, p. $\eta^2 = .16$ (see Fig. 8). Predefined contrasts showed that students had significantly higher error rates on the second problem, compared to the first problem, $F(1, 84) = 11.62$, $p < .001$, p. $\eta^2 = .12$. We attribute this to the second molecule (CO_2) being more complex than the first (CH_4) because—in contrast to the first, it contains double bonds and lone electrons. Compared to the respective previous problems, students had significantly lower error rates on the third problem, $F(1, 84) = 42.79$, $p < .001$, p. $\eta^2 = .34$; on the fourth, $F(1, 84) = 9.30$, $p = .003$, p. $\eta^2 = .10$; on the fifth, $F(1, 84) = 21.37$, $p < .001$, p. $\eta^2 = .20$, and on the sixth problem, $F(1, 84) = 5.52$, $p = .021$, p. $\eta^2 = .06$. In sum, these results show that error rates decreased across problems, indicating that students became more proficient at drawing Lewis structures.

Second, we tested whether students' error rates decreased across problems with ball-and-stick models. A repeated measures ANOVA with the two ball-and-stick model problems as repeated factor and the number of errors made per problem in drawing a ball-and-stick model as dependent variables showed a large

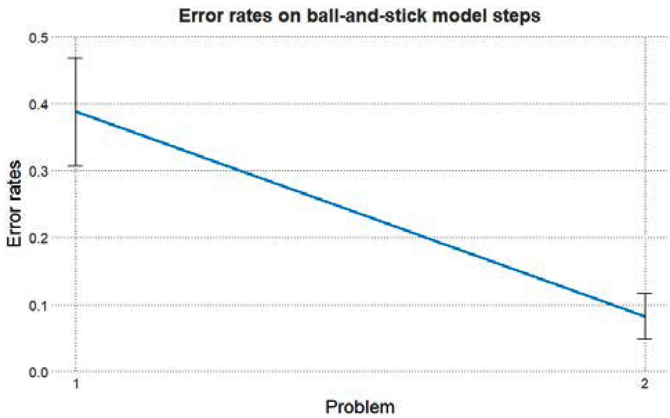


Fig. 9. Error rates across problems in which students draw ball-and-stick models. The y-axis shows the number of errors in drawing a correct ball-and-stick model in each problem. The x-axis shows the sequence of problems with ball-and-stick models. A decrease in error rates indicates that students became more proficient at drawing ball-and-stick models.

significant effect of problems, $F(1, 84) = 13.35$, $p < .001$, p. $\eta^2 = .14$ (see Fig. 9). In sum, this shows that students became more proficient at drawing ball-and-stick models.

Finally, to examine students' ability to transition between the visual tools, we compared error rates between the visual tools. Error rates on ball-and-stick models were significantly lower than on Lewis structures, $F(1, 84) = 52.07$, $p < .001$, p. $\eta^2 = .38$. Given that students tend to have more experience with Lewis structures than with ball-and-stick models and given that the molecules students built with ball-and-stick models were no less complex than those they built with Lewis structures, this suggests that students transferred their knowledge of Lewis structures to ball-and-stick models.

Learning of chemistry knowledge. To explore whether students' could use the visual tools to learn chemistry content, we first tested whether students showed significant learning gains in the two weeks in which they used Lewis structures. For the first Lewis structure week, a repeated measures ANOVA with the three chemistry tests (i.e., pretest, immediate posttest, delayed posttest) as repeated factor and students' test scores as dependent variables showed a medium significant effect of test, $F(2, 168) = 8.87$, $p < .001$, p. $\eta^2 = .10$. Post-hoc comparisons showed that these gains were significant from pretest to immediate posttest, $F(1, 84) = 10.11$, $p = .002$, p. $\eta^2 = .11$, and from pretest to delayed posttest, $F(1, 84) = 15.32$, $p < .001$, p. $\eta^2 = .16$. For the second Lewis structure week, results showed a medium significant effect of test, $F(2, 168) = 5.60$, $p = .004$, p. $\eta^2 = .06$. These gains were significant from pretest to immediate posttest, $F(1, 84) = 16.13$, $p < .001$, p. $\eta^2 = .16$, and from pretest to delayed posttest, $F(1, 84) = 2.44$, $p = .03$, p. $\eta^2 = .03$.

Second, we tested whether students showed significant learning gains when they used ball-and-stick models. An ANOVA showed a medium significant effect of test, $F(2, 168) = 9.41$, $p < .001$, p. $\eta^2 = .101$ that were significant from pretest to immediate posttest, $F(1, 84) = 6.70$, $p = .011$, p. $\eta^2 = .074$, and to delayed posttest, $F(1, 84) = 18.31$, $p = .001$, p. $\eta^2 = .179$.

3) Discussion: Results indicate that students who worked with a combination of our Lewis structure and ball-and-stick model tools became more proficient at drawing visual representations across practice opportunities. This finding suggests they learned representational competencies allowing them to visualize information about molecules while conforming to drawing conventions in chemistry. Importantly, we found no evidence that transitioning between the tools impeded students' gains in proficiency. This replicates the user study in a realistic setting and suggests that the button design resolved a design tradeoff between different functionalities in the visual tools.

In addition, results showed significant improvements from pretest to posttest. Students retained these gains in the following week. Given that our study did not include a control group that did not use these tools, we do not know to what extent these gains are caused by the visual tools themselves. Nevertheless, the results indicate that students' use of the visual tools was associated with lasting learning gains of chemistry knowledge typically taught via problem-solving activities that ask students to interact with Lewis structures and ball-and-stick models.

In sum, this study expands prior research on transfer [9], [33], [34] by revealing boundary cases for positive and negative transfer in the design of educational technologies. Similarities in the design of the tools enhanced positive transfer that helped students transition from the Lewis structure tool to the ball-and-stick model tool. Changing the design of the buttons so that they were sufficiently dissimilar prevented negative transfer when students realized that the atom placement tool in the ball-and-stick model added atoms, not electrons. Enhancing positive transfer while preventing negative transfer reduces the potential for students' confusion when they work with visual tools and hence increases the cognitive capacity available for learning.

VII. General Discussion

In this article, we investigated how to design interactive visual tools for educational technologies. Instruction in most STEM domains asks students to interact with visual representations while solving problems to learn content knowledge. Educational technologies offer advantages over traditional paper-based drawings by providing immediate feedback on students' representations, which helps them (a) to construct visuals that align with disciplinary conventions and (b) to use visuals to learn about concepts. We presented a design-based research project that sought to address design tradeoffs that emerged during the development of interactive visual tools.

One design tradeoff results from the fact that educational technologies should, on the one hand, help students succeed in problem solving by increasing usability. Designers can increase usability by preventing mistakes that could interfere with learning. On the other hand, designers have to distinguish usability issues from learning opportunities. Educational technologies should allow for mistakes that present important learning opportunities. Study 1 compared experts and novices to identify design tradeoffs between nonessential mistakes that students make in drawing Lewis structures that a visual tool should prevent and essential mistakes that visual tools should allow. As a principle, we propose that visual tools should allow mistakes if they meet one or more of the following conditions:

1. If the mistake indicates that students do not know drawing conventions that are common among experts (e.g., mistakes in drawing atom symbols);
2. If the mistake indicates that students do not know how to use information from other resources to inform the drawing (e.g., using information from the periodic table);

3. If the mistake indicates that students do not understand a domain-relevant concept (e.g., bond order).

Not only should the visual tool provide opportunities for these types of mistakes, it should also provide corrective feedback and make it easy for students to modify the visual features in their drawings that correspond to these mistakes. By contrast, we propose that visual tools constrain functionalities in ways that mistakes that are not essential but are prevalent and time consuming (e.g., aesthetic aspects). Constraining these aspects allows students to focus on the essential aspects of the drawing task and may thereby enhance learning efficiency.

A second design tradeoff results from students often having prior experiences with visual tools that vary in usability. These experiences may lead students to expect functionalities that can be suboptimal because they may not match usability considerations for the given problems. Study 2 used iterations of user testing and redesign to identify design tradeoffs between usability for students with and without prior experiences with visual tools. We identified functionalities that caused confusion if students had conflicting expectations based on prior experiences. While some of these expectations revealed some advantages of alternative designs, others impeded students' learning from essential mistakes. Hence, as a general principle, we recommend that designers purposefully include students who may have conflicting design expectations based on prior experiences with visual tools in user testing. We found that simple tweaks to instructions were sufficient in communicating the functionality to students. This not only improved the usability but also students' learning from mistakes.

A third design tradeoff results from the fact that instruction in most STEM domains relies on multiple visuals. Consequently, students need to easily transition between tools. On the one hand, different visual tools require different functionalities. On the other hand, the functionality of the tools should align so that students can transfer from one to the other. Study 3 identified tradeoffs between usability considerations for each visual tool and alignment considerations across visual tools. We found that students may mistake visual similarity of features across tools as indicating similar functionalities. This can lead to confusion that could prevent learning if these similarities are incidental. By contrast, implementing corresponding actions (e.g., atom placement) by different functionalities (e.g., typing versus menu-based selection) can prevent such confusion.

VIII. Limitations and Future Directions

Our contributions should be interpreted in the context of several limitations. First, we situated our research in chemistry. We found this context useful because visuals are prevalent in chemistry and often pose an obstacle to students' learning. Further, delayed feedback on paper drawings poses an obstacle to their learning. We believe that both aspects are representative of STEM instruction; for example, biology students often draw to learn about concepts ranging from anatomy to cell structure. Consequently, it seems likely that examining differences between expert and novice drawings in other domains will also reveal mistakes that present opportunities for learning drawing conventions as well as mistakes that should be prevented because they are distracting. Further, a variety visual tools exist for other STEM domains, and it seems likely that prior experience with tools may affect students' expectations in these domains. Finally, most STEM domains use multiple visuals, so that students will benefit from tools that allow for easy transitions. Nevertheless, future research should examine if our findings generalize to other STEM domains.

Another limitation regarding the generalizability of our findings results from our choice of population. Our target population were college students. While we see no reason why our results on design tradeoffs should not generalize to younger students, we believe additional factors may need to be considered for younger populations. In particular, opportunities to learn from mistakes might have to be more carefully designed for younger students who may get more easily discouraged. Hence, future research should investigate whether visual tools for younger students should consider affective factors. Also, students in our studies were paid for their participation. This stands in contrast to students who use visual tools for their own learning. Hence, future research should investigate if our results generalize to more realistic situations.

A further limitation regarding generalizability stems from the methodological choices we made in each study. Specifically, we chose to ask students to draw visuals in sequences that corresponded to sequences that we found to be common in chemistry instruction. Further, in the observational classroom study, we embedded the visual tools in an instructional sequence that included other resources such as videos. It is possible that these sequences might have affected our findings. Therefore, future research should examine whether our findings apply to visuals used in other instructional sequences.

Finally, a limitation results from our focus on virtual visual tools. Many STEM domains include physical manipulatives that students use to solve problems. A recent focus of educational technology research is to incorporate physical manipulatives in instruction and to integrate them with virtual functionalities that can provide feedback on students' interactions with physical manipulatives [1], [6]. This creates new design challenges because physical manipulatives have built-in constraints that may limit opportunities for students to make mistakes. For example, in physical ball-and-stick models, spheres that show atoms have holes into which students can put only a limited number of bonds. Therefore, the physical model constrains students to a limited number of bonds, and therefore they cannot learn from making the mistake of adding too many bonds. Future research should examine how virtual functionalities can add learning opportunities to physical manipulatives that may not allow for certain types of mistakes.

IX. Conclusion

Our design-based research project identified tradeoffs in the design of visuals for educational technologies. Our study suggests several steps to resolve these tradeoffs. First, designers should carefully weigh goals revealed by expert-novice comparisons so that visual tools allow mistakes that present opportunities to learn drawing conventions. Second, designers should compare students with and without prior experiences to identify expectations that may hinder learning. Third, designers should ensure that one visual tool is designed in a way that facilitates transitioning to another visual tools, as STEM instruction typically involves multiple visual representations. Given that in many STEM domains, learning hinges on students' ability to understand and manipulate visuals to solve domain-relevant problems, we believe our findings may have a significant impact on educational technology design.

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