The Lewis Structure explorer: Accessible by Design

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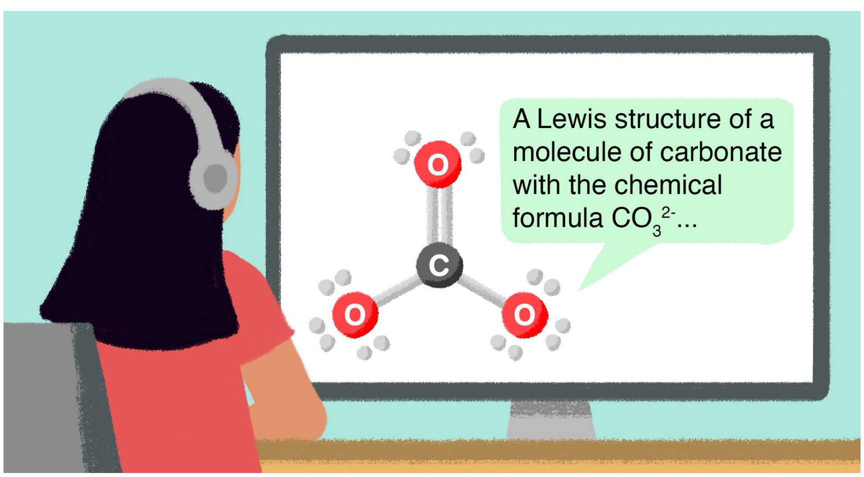
ABSTRACT

Successfully learning principles from drawing Lewis Structures sets the foundation for understanding more complex representations of chemical concepts. As these visual-based concepts are core competencies in chemical pedagogies, it is incumbent and required for educational institutions and faculty to provide usable accommodations for all students, including those with blindness and low-vision (BLV). The shift to visually based interactive digital media increases the technical challenge for addressing accessibility for BLV students and makes creating these accommodations by faculty even more difficult. This technology report presents research and development for providing a digital learning system for Lewis Structures designed to be directly accessible by BLV students and other screen reader users. This Lewis Structure explorer can be used by all students and includes a form-driven keyboard accessible control panel. The alternative (alt) text for the structural representations is generated dynamically with user input. The results from two usability studies, one with over 300 sighted college students and the other with four BLV adults who depend on alt text for non-text information, are presented.

Graphical Abstract



KEYWORDS

High School/Introductory Chemistry, First Year Undergraduate/General Chemistry, Curriculum, Multimedia-based Learning, Computer-based learning, Accessibility

The path for students to develop competence in the wide variety of visual representations in chemistry generally begins with learning Lewis Structures, and it is here where many students lose their way.[1] The Lewis Structure explorer was designed to give students real-time feedback while drawing Lewis Structures with a digital interactive tool, Figure 1. The interactive provides visual feedback using trackers as atoms and electron-groups are added to the screen with a drag-and-drop interface. These trackers, shown in the upper right corner of Figure 1, can be turned on or off by the user and display formal charge, octet count, and number of electrons placed through the addition of bonds and lone pairs. There was, however, an ethical issue with the initial design of the interactive: it was virtually inaccessible to students with blindness or low vision (BLV). The drag-and-drop interaction model is one that is specifically described in the Web Content Accessibility Guidelines (WCAG) as not meeting accessibility standards.[2] General guidance for interactives in WCAG is weak as it falls in an ambiguous area. Creating truly accessible systems which depend on direct user input in real-time is more technically difficult than, for example, providing closed captioning for videos or descriptions of animations.[3] Developing new methods for providing direct accessibility as part of the interactive user interface was the goal of this project.

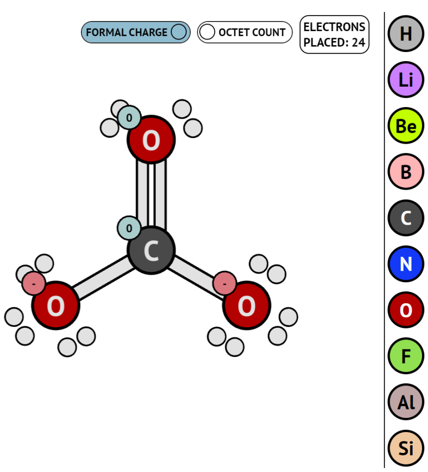


Figure 1: A screenshot of a carbonate ion made in the Lewis Structure explorer

This article describes the research and design principles that were utilized in re-creating the interactions and the visual information displayed in the Lewis Structure explorer so that it could be used independently by BLV students, and also support chemistry faculty members as they create inclusive and accessible learning experiences for all their students. Presented are desciptions of two of the three parts which, when combined, create the accessible digital interface for the Lewis Structure interactive. This interface delivers information through the user's screen reader and does not require additional hardware. First, a systematic method was designed to dynamically generate descriptions of what is created in the interactive. These descriptions are used as alternative (alt) text which are used with a screen reader to understand visual content. Second, a keyboard accessible control panel was co-designed with a BLV user for an intuitive interface which works with screen reader software. Third, an artificial intelligence (AI) interface was created so that a BLV user could personalize their learning experience, and is reported elsewhere.[4] Two studies were conducted with these interfaces to investigate usability. The goals of this report are to share lessons learned with the broader chemistry education community to bring attention to and inspire collective creativity in solving the problem of general inaccessibility of chemistry and chemistry teaching tools within current pedagogical practices.

The Case for Accessibility and UDL

In the United States, all universities that receive federal funds or financial aid must meet civil rights laws for accessibility.[5] Legal requirements on universities are driving an increase in awareness for accessibility, so in the classroom, faculty require additional materials and support to meet the accessibility needs of their students.[6] Additionally, the promise of outcomes from visually rich interactives for the general population of students may be stymied without accessible user interfaces. Increasingly, university procurement offices are challenging adoption of digital tools that do not meet accessibility standards.[7]

An approach for creating inclusive accessibility solutions is outlined with the Universal Design for Learning (UDL) framework to eliminate systemic barriers to success by using multiple means for "engagement, representation, and action" thus matching the widest possible range of users' needs.[8] It was previously reported that one such UDL-designed interface for chemical particulate concepts, which used tactile manipulatives recognized by computer vision algorithms, provided an accessible input method for the chemistry interactives in a K-12 educational setting.[9] Though useful for foundational spatial concepts, this multi-sensory interface is limited by the need for external hardware (a webcam, magnetic whiteboard, and the manipulatives). A digital-only interface was desired to overcome these limitations and to provide a more scalable solution for building additional accessible digital interactives.

DESIGNING USABLE ACCOMMODATIONS

Application of the UDL framework to a digital-only solution for BLV students helped identify the primary goals of the research and development for this project to be:

1) Develop a dynamic alt text generator for the Lewis Structure explorer
2) Develop an interface that does not require memorizing keyboard controls

Another requirement was that the system for alt text generation and the keyboard accessible interface was not specific for the Lewis Structure explorer and could be reproduced for other learning objectives and interactives. Access to the Lewis Structure explorer and a series of activities which use the explorer can be found at the authors' website.[10,11]

Dynamically Generated Alt text

The first step in designing a system to generate alt text dynamically was to review standards and best practices for writing alt text.[12-15] The most influential recommendation was the National Center for Accessible Media's (NCAM's) Drill-Down Organization method which states best practices are to provide "a brief summary followed by extended description and/or specific data."[15] The first author applied the Drill-Down method to devise a "fill-in the blank" type script for describing Lewis structures. The second author then developed software that could compose text based on information from the configuration data generated by the interactive. For example, in the Lewis structure interactive for each atom the configuration data captures the identity, charge, bonds, lone pairs, and position.

The resulting descriptions were tested with a variety of use cases and the alt text script was iterated as needed. Once there was internal consistency of the results, the alt text was tested with a consultant who is blind and regularly listens to alt text. This feedback was then used to clarify the alt text descriptions and improve them further. The result was alt text that is presented in a consistent format that follows best practices and appropriately applies chemistry terminology. (Examples of these alt text descriptions are included in the Supporting Information (SI).)

Keyboard Accessible Control Panel

The initial accessibility interface used specific keyboard commands, as is recommended by WCAG. However, when this interface was tested with the BLV consultant, it became clear that the interface was not user friendly. The commands were hard to remember and little to no feedback was provided to inform the user when actions were successfully done. Through brainstorming sessions with our BLV consultant, we hypothesized that a form-based method (dropdowns, buttons, and numeric stepper) for controlling the explorer with the keyboard would be more intuitive. The order of the form also could follow the drilldown script for the alt text logic system. A second benefit to following the alt text logic system was that it was straightforward to extract the alt text for a specific component and re-word it slightly to give a useful description of the action that had been triggered by the form. Additionally, a button was included to deliver the dynamically generated alt text of the current drawing so users could check their progress as needed. The BLV consultant tested prototypes of the keyboard accessible control panel (KACP) and gave feedback for iterative development. This co-design process was essential to creating the prototype.

USE STUDIES

Success of the descriptions and KACP was measured through a usability and feasibility study with the Lewis structure explorer serving as the proof of concept for the method. Prior to recruitment, all procedures were reviewed and approved by HML IRB (study #2146). User tests were conducted with 318 sighted chemistry college students and four BLV adult users. As it is not common practice for BLV individuals to produce images themselves, the sighted participants were asked to build Lewis structures within the interactive based on the dynamically generated alt text descriptions. This provided authentic representations of mental visualizations constructed based on the descriptions. Then, BLV users were presented the alt text and asked to decide which one of three tactile diagrams matched the description. The distractors were based on the images produced by the sighted users. After testing the alt text, BLV users were guided on how to use KACP to build a simple molecule and were asked to build a second molecule independently.

Study with chemistry college students

Participants for the user test were college students enrolled in a chemistry course and who were 18 years or older. Students were instructed that their goal was to construct the Lewis structure in the interactive based on the description, regardless of whether the described structure was chemically feasible. There were ten descriptions, with half of the structures not feasible to ensure drawings were based on the alt text and not chemical intuition.

Of the valid structures submitted, 81% were correct. (Data from this study are provided in the SI.) Across all the structures, most of the incorrect responses submitted had the correct basic skeletal structure. The errors were related to finer details, such as the number of lone pairs or formal charge label on an atom, all of which are included in the alt text. Therefore, these findings indicate the alt text is satisfactory for creating an accurate visual.

Study with BLV users

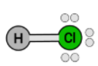
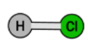
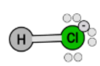
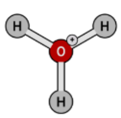
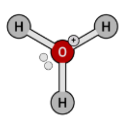
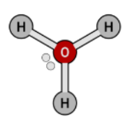
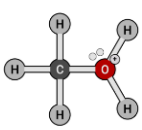
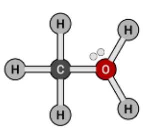
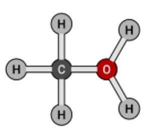
Four BLV adults who regularly use a screen reader and rely on alt text to access non-text information in digital media participated in the second study. This number of participants was deemed sufficient to detect the majority of usability problems.[16] Participants were asked to complete three problems where they had to pair alt text to one of three tactile Lewis structures. Participants were not given any information about the pattern or structure of the alt text so that it would be roughly equivalent to encountering a description within a learning tool for the first time. After each problem a series of Likert-scale questions were asked to gauge the quality of the alt text and a semi-structured interview after the usability study provided further insight into participants' satisfaction.

All participants identified the correct tactile structure for each problem giving a success rate of 100% across all participants. Further, for each problem all participants either agreed or strongly agreed with the statements: I am confident in my choice, it was easy to select the diagram, the description was clear, I am satisfied with the description provided (Table 1).

During the interview participants expanded on their impressions of the alt text. In comparison to prior experiences with alt text one participant noted the clarity provided by the consistent descriptions. "The biggest problem I've always had with anything electronic is inconsistency. So looking at image to image the alt text doesn't follow the same pattern, there don't seem to be rules for the alt text, [but] this was very consistent, with very consistent rules.” Along with consistency participants highlighted the alt text had a nice structure, “I liked the flow of it, that it gave me the general chemical formula then the specific components,” and appropriate amount of information, “it had enough detail to understand but didn’t overload you with information.”

Another participant highlighted the appreciation that it sounded like alt text that was written by someone who was both knowledgeable about and how to explain it so that anyone can understand. “It seemed like it was created by someone who was knowledgeable but not so knowledgeable that they were using terms that were unfamiliar, like it was accessible to the layperson but it also used proper terms and was applicable.” Overall, participants reported satisfaction with the quality of the alt text even though two self-reported that they are usually harsh critics when testing technology made for the BLV community.

Table 1: Structures used and results from testing the auto generated alt text. Participants scored their agreement with the statements using a 5-point scale where 1 is strongly disagree and 5 is strongly agree.

Structures presented to BLV users as potential matches to alt text A	B	C	% users who selected correct structure	I am confident in my choice	It was easy to select the diagram	The description was clear	I am satisfied with the description provided
			100	4.5	4.75	4.25	4.5
			100	5	4.75	4.75	5
			100	4.75	4.75	4.25	4.5

Next, the BLV users were given the opportunity to build using the KACP. To learn how to use the control panel participants were guided by the interviewer through a step-by-step process to draw ammonia, NH_3. One participant requested to try to use the control panel without any tutorial guidance and was able to build ammonia by only asking a couple of questions. On average, participants spent approximately 10 minutes going through the tutorial. During the tutorial participants voiced appreciation that after clicking a button that triggers an action, the system’s ability to describe the action's result increased their confidence. The feedback allowed them to check their work as they built and to experiment to learn what each button did when clicked. As one participant explained, "You need time to work with something to make mistakes and learn what is good and bad before it works well and I was able to use like it almost instantaneously so that was very cool" and the feedback made that process quicker.

Once participants had all their questions answered they were given a tactile diagram and description of formaldehyde (Figure 2) and asked to draw it independently in the interactive. All participants independently used the controls and feedback to successfully build formaldehyde. Without prompting, every participant clicked on the button that reads the dynamically generated alt text to confirm the structure was complete and matched the tactile diagram. One participant finished in less than 2 minutes, two finished in under 4 minutes, and the last took about 10 minutes. When asked to rate the difficulty of using the drawing tool on a scale of 1 to 5 where 1 is very difficult and 5 is very easy, three of the four participants said easy or very easy. These findings confirm that the form-based accessible interface was usable, but perhaps more insightful were the interviews with participants. The interviews highlighted how this form-based approach for an accessible user interface was novel. One participant remarked, "You could drop the whole science thing, move on to drawing in general, go into architecture."

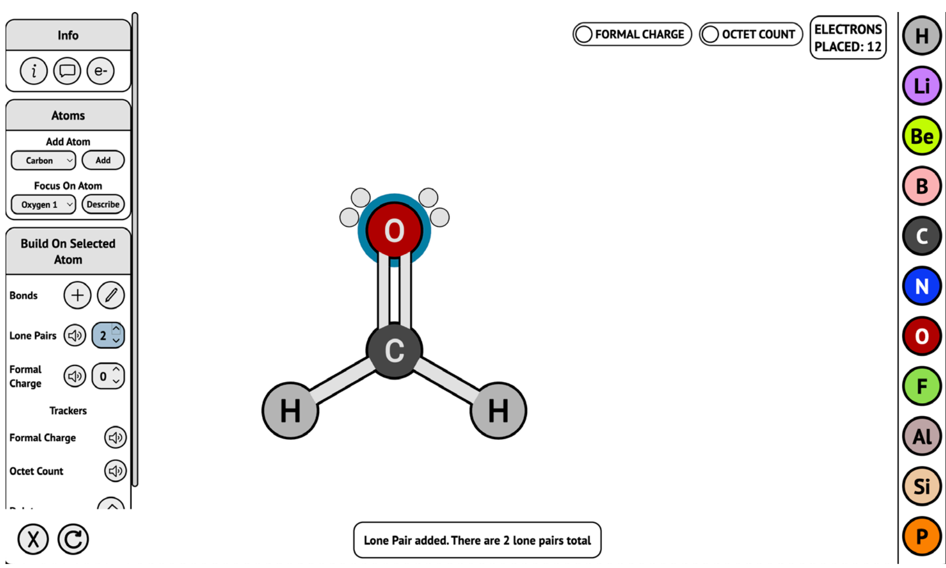


Figure 2: Molecule built using accessible controls

When asked “what was your favorite thing about the drawing tool’s controls” two mentioned the form-based design. Along those lines another participant highlighted the combo boxes and dropdown menus as easy to use with a screen reader and that the buttons were clearly labeled. The rapid feedback, made possible by the alt text generation system, was also highlighted as important for usability. Overall, this participant was positive by how smoothly the control panel worked and requested “Whatever code you used to make this accessible control panel just keep it and use it and replicate it.” Beyond usability, two participants stated it was gratifying that they could draw something themselves for the first time. One participant requested an export button, so that the drawing could be readily shared with instructors or peers. All participants were pleased with what they could accomplish with the accessible chemical drawing system.

A major hypothesis that inspired development of a form-based control panel was that replacing a mouse with keyboard commands, while standard practice to meet accessibility standards, is not easy for BLV users to learn or apply. We asked participants to compare using the menu with a program that requires keyboard commands. One participant explained that

> …it goes faster when you have those keyboard commands. But when you don’t know it well, having to know keyboard commands is more tedious. Being able to navigate menus is better. So, if this was something I was going to use every day of my life, if I was going to be a Lewis structure builder, I would want keyboard commands but if it’s something I’m going to use once in a while, for like a single unit [as in school], I think that the menu system is much better.

The quote supports our hypothesis that asking students to memorize keyboard commands for a learning tool that will only be used for a short time is unfeasible. One participant was in college and when asked if she thought it was easy enough to learn to use even for one small unit in a whole course, and college courses move fast, she said yes. Not only did the form-based control panel enable participants to draw a Lewis structure, but it also gave some their first experience with building and interacting with diagrams like “a normal person,” (a participant’s own words) providing a perspective that those of us who are sighted often take for granted in our ever increasing visually centered digital world.

FUTURE WORK

The reported studies were focused on usability of the Lewis Structure explorer's interface. Due to the low-incidence of the BLV population, which number less than 0.5% of student population in K-12,[17] and is even a lower incidence population in college-level chemistry due to the BLV students steering away from STEM courses,[18] group-based research studies for establishing the promise of outcomes for a learning tool with BLV students are not feasible. Single case design (SCD) methods, where BLV indivuals serve as their own controls and the introduction of an intervention (the learning tool) is staggered across a small sample of participants, are more appropriate for this population.[19] Two SCD studies are planned with K-12 BLV students using accessible interfaces. These next studies will also be used to demonstrate the feasibility for inclusive use of the accessible interfaces for a BLV student within a general population classroom.

The accessibility system with the dynamically generated alt text and the form-based control panel has been integrated into five other digital explorers: three for chemistry (VSEPR, a particulate reactions explorer, and an organic chemistry sketcher), one for physics (optics), and one for elementary school math. The accessible VSEPR and particulate reaactions explorers are also available on the author's website.[20,21] Development has commenced on expanding the initial limited scope of the organic chemistry sketcher to provide an accessible and inclusive method for BLV students to learn and study independently in college-level organic chemistry. The AI integration for personalized exploration is being integrated into other digital explorers, with early results of this development reported at an AI-focused proceeding.[4]

The diagram export button requested by one of the study participants to provide a means of communication for BLV students also allows instructors a method for creating chemical drawings that include standardized alt text for use in their teaching practice. This feature is being designed so that the alt text is directly included in the meta-data of the image, thus creating a much needed system for producing usable alt text for chemical images. The multiple use cases for a single accessibility feature demonstrates the promise of using Universal Design for Learning as a framework for developing educational technology which is accessible-by-design and usable by all.

ASSOCIATED CONTENT

Supporting Information

Supporting information (.pdf): Includes sample alt text descriptions, the data from the usability study with sighted students, and a guide to using a screen reader

The Lewis Structure explorer: https://www.alchem.ie/lewis-structures

A sample activity using the Lewis structure explorer: https://www.alchem.ie/blog/lewis-structure-activity

The VSEPR explorer: https://www.alchem.ie/vsepr

The Reactions explorer: https://www.alchem.ie/reactions

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ACKNOWLEDGMENTS

The authors want to thank Nicole Kada, for her constructive and detailed feedback on both the alt text that was developed and in helping to co-design the Keyboard Accessible Control Panel, which we fondly call, “Nicole’s Controls.” The authors want to acknowledge team members who helped to create the Lewis Structure and other accessible digital explorers: Joe Engalan, Jacob Zysnarski, Katherine Rochon, Ben Stimpson, and Gianna Manchester. This material is based upon work supported by the National Science Foundation, Grant #2221722, through the Small Business Innovative Research program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

CONFLICT OF INTEREST STATEMENT

The authors have received compensation for work performed as employees of Alchemie Solutions, Inc, the producer of the Lewis Structure explorer and other digital learning tools mentioned in this manuscript.

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