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Leveraging an App to Support Students with Color-Vision Deficiency and Color-Blindness in Online General Chemistry Laboratories

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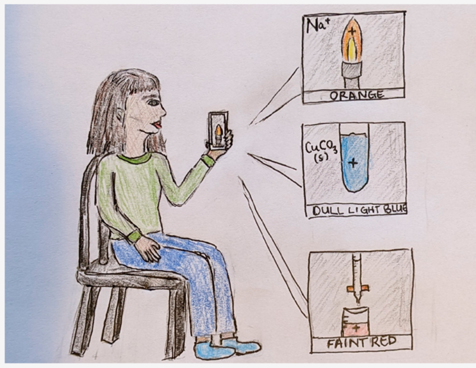
ABSTRACT: Assistive technologies remain important in supporting student learning in both in-person laboratories and the online laboratory environment. In this article, we describe an adaptation of a smartphone technology called the Color Blind Pal app to aid students in complementing online laboratory assignments in a general chemistry course. The app was integrated into three online laboratory experiments to help students collect data from simulated flame tests, atomic emission spectra, precipitation reactions, and colorimetric titrations. We share how incorporating the app has influenced our perspective on inclusive practices in the online lab curriculum as the app allows both users with color-vision deficiencies or color-blindness to make color observations and for instructors to simulate color-vision deficiencies when designing curricula. Given our use of the app as an assistive technology, we discuss implications for a shift toward universal design for learning (UDL) to proactively design inclusive online laboratory curricula.



KEYWORDS: *General Public, First-Year Undergraduate/General, Curriculum, Laboratory Instruction, Computer-Based Learning, Internet/Web-Based Learning, Distance Learning/Self Instruction, Descriptive Chemistry, Minorities in Chemistry*

Color is intrinsic to the practice of chemistry, so much so that one would be hard-pressed to find a general chemistry curriculum which does not address visible light. For example, spectroscopy, a fundamental instrumentation practice, leverages color to find the concentration of a solute in a solution. Likewise, chemists make use of color to identify certain elements and compounds; all safety data sheets (SDS) contain a color description of the chemical. Color-based observations are inherent to making observations in chemistry; therefore, instructors need to attend to the different ways in which students may perceive color for all students to have access to meaningful participation in chemistry courses.

With many courses turning to online learning modalities for laboratory coursework throughout the COVID-19 pandemic,[1,2] chemical educators need to consider the accessibility of new and adapted online laboratory curricula.[3,4] Chemistry instructors, particularly those assigned to teach introductory-level courses, should proactively consider how all students can access and engage with materials and learning opportunities when designing coursework. For example, instructors can use universal design for learning (UDL) guidelines to embed accessibility within course materials through opportunities for rich and varied engagement with chemical concepts.[5] One particular issue in visual perception in a chemistry course is color-vision deficiency or color-blindness (hereafter color-vision deficiency). (The author does not identify as having a color vision deficiency. As the author is not a member of this community, a concerted effort was made in the manuscript to use person-first language per the Inclusive Language Guidelines available through the APA (https://www.apa.org/about/apa/equity-diversity-inclusion/language-guidelines). At the time of publication, the author had not been able to discern whether the community prefers person-first or identity-first language. The author elected to use color vision deficiency instead of color-blind to accurately describe the many types of color vision deficiency.) For students with color-vision deficiencies, in-person laboratory coursework can present some barriers to collecting and interpreting data;[6−9] however, barriers for students with visual disabilities may be magnified in online settings.[10,11] For example, a Reddit search revealed student concerns about whether they can continue in chemistry if they have a color-vision deficiency.[12]

COLOR-VISION DEFICENCY IN CHEMISTRY EDUCATION

The incidence of color-vision deficiency is estimated to be 0.5% of females and 8% of males in the population.[13,14] Color-vision

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Table 1. Online Experiments in Which Color Blind Pal App Was Used

Experiment Name	Description of Activities	
Exploring Atoms through Flame Tests and Atomic Emission Spectra	Activity 1: Flame tests	Burn ionic solids in open flame
	Activity 2: Atomic Emission Spectra	Examine atomic emission spectra of gases
Precipitation Reactions	Activity 1: Observing Precipitation Reactions	Students mix ionic solutions in test tubes and observe colors of precipitates
Techniques to Determine Concentration: Titrations	Activity 1: Titrations	Students perform strong acid strong base titration with phenolphthalein as indicator
	Activity 2: Concepts in acid/base titrations	Students perform strong acid strong base titration with bromocresol green as indicator

deficiency produces confusion around the perception of different colors depending on one's color-vision deficiency type. Deuteranopia, colloquially know as red−green color-blindness, is most common, and tritanopia produces confusion with blue and yellow colors.[13] About 1 in 30,000 people are affected with achromatopsia, a condition where only black, white, and gray are seen and affected.[15] In an introductory chemistry course with an enrollment of 1000 students, if 500 are male and 500 female, 40 male students and 3 female students may have color-vision deficiencies. Thus, color-vision deficiency is a prevalent, but underconsidered, visual disability that many students experience. These vision disabilities are often not reported, but they affect students in the general chemistry curriculum and beyond.[9]

Equitable access of laboratory materials for students with color-vision deficiency has been discussed in the chemical education community in the instance of interpreting colorimetric titration end points.[6] Recently, researchers reported the use of assistive smartphone technologies to aid students with color-vision defficency and low vision in the in-person lab.[16] Adaptations have been designed for use in titrations such as the Titration ColorCam[17] and automated titrations with text to speech capabilities.[7] These applications beep and vibrate when the titration end point has been reached and help students with color-vision deficiencies and visual impairments in making observations and collecting data in in-person laboratories. Discussion in this *Journal* to support students with visual impairments in online chemistry laboratories has focused on blind and low vision (BLV) learners.[18] For students with color-vision deficency, the ACS manual *Teaching Chemistry to Students with Disabilities* advises the following: Web-based activities need text equivalents provided of the graphics content that students are intended to observe.[19] For vision-impaired learners, D'Agostino[18] advises "the primary goal is to enable them to become independent workers by providing access tools that will create the least restricting learning environment".[18]

There are many options available online for web-based design to address color-vision deficiency. The Color Oracle software adjusts desktop display to simulate color-vision impairment. For those who have color-vision deficiency, the Visolve software adjusts color saturation to make colors more legible to students.[20] Additionally, several app-based smartphone-based technologies such as Color Blind Pal[21] and ColorAssist Lite[22] provide a text readout of colors captured through smartphone cameras.

■ ONLINE GENERAL CHEMISTRY LABORATORIES IN THE COVID-19 PANDEMIC

Like many chemical educators in the continuing COVID-19 pandemic, the general chemistry laboratory course we instructed needed to be offered online. The purpose of laboratories in the online format had to be reassessed in the general chemistry curriculum while simultaneously providing meaningful access and opportunities for participation to students with[23] and without disabilities.[1,24]

At Purdue University, chemistry courses are organized by major. Our course is designated for students in the health sciences and agriculture, and for students seeking to fulfill a general education science elective, and was slated as an online-only laboratory for the Fall 2020 term. Course enrollment was approximately 1100 students. We turned to online modalities for our course and integrated experiments in the Beyond Labz[25,26] platform and various other web-based activities into the course. Prior to the pandemic, students would work in collaborative groups under the guidance of teaching assistants. In Fall 2020, students were faced with navigating laboratory experiments asynchronously and individually.

With the shift to online instruction, our learning objectives and the modality of experiments also changed. Previously, a large part of the laboratory course was dedicated to teaching basic hands-on laboratory skills. Without the in-person lab to teach these skills, we had to reimagine the goals of the laboratory. We replaced laboratories that were dedicated to teaching lab techniques with labs designed to support students' content learning and the interpretation of laboratory data. Before the pandemic, students may have achieved sense-making through tactile modes in the lab; now, they were sense-making in a virtual environment which required data collection mainly via visual methods.

■ STUDENTS WITH COLOR-VISION DEFICIENCY IN OUR COURSE

Prior to the pandemic, students with color-vision deficiency in our course worked with peers in the laboratory to aid in evaluating color and a TA who could facilitate their learning. Teaching assistants interacted with students each semester who reported color-vision deficiencies when we performed titrations in the lab. In those situations, students could rely on their lab partner to make observations about the end point in the titration.

With the shift to online laboratories, we filled in gaps left by hands-on skill development laboratories in our curriculum with online lab simulations such as flame tests (Table 1). We were excited to have the opportunity for students to perform simulated experiments that were inaccessible in the in-person lab due to safety or cost. Early in the semester, one of our teaching assistants shared during a staff meeting that one of their students was struggling to make qualitative observations in the online laboratory assignments due to collecting color-based observations. Unlike low vision disabilities, color-vision deficiencies are more likely to remain under-reported as disabilities. Therefore, like many other chemical educators, we

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did not know how many students have some form of color-vision deficiency in our courses. Emblematic of the problems of accessibility for marginalized students that have arisen due to the pandemic,[3] we realized that the online laboratory curriculum we had designed was not sufficiently accessible for students with color-vision deficiencies. There are several existing technologies designed for blind and visually impaired (BVI) students which also work well for students who have color-vision deficiencies.[7,17] These apps are designed for specific lab experiments in the in-person lab environment and are difficult to integrate into online simulations.

We considered several assistive technologies for color-vision deficiencies such as Visolve which enhances colors on screens to make them more distinct;[20] however, Visolve did not provide an alternative mode by which to make color assessments that would allow students to read the colors in the display as is recommended by the best practices literature for learners with visual impairments or color-vision deficiencies in chemistry.[18,19] To support students with color-vision deficiencies we leveraged the Color Blind Pal app.[21] The Color Blind Pal app allowed students to point their phone camera at anything, freeze the screen, and adjust the target on the screen, and then it provides a text readout of the color of the item being targeted as shown in Figure 1. The app is also available on Mac OS for a fee.[21] An alternative technology to the Color Blind Pal app is the Color Assist Lite app which is only available for Apple products. We wanted the technology to be accessible to students in the course so we opted for the Color Blind Pal smartphone-based app as many students have smartphones but not all students had Apple products. The Color Blind Pal app also allows users with normative vision to adjust the colors in the camera to simulate a variety of color-vision deficiencies. In designing the curriculum, we found this to be particularly exciting because it allowed us to view the laboratory assignments from the perspective of students.

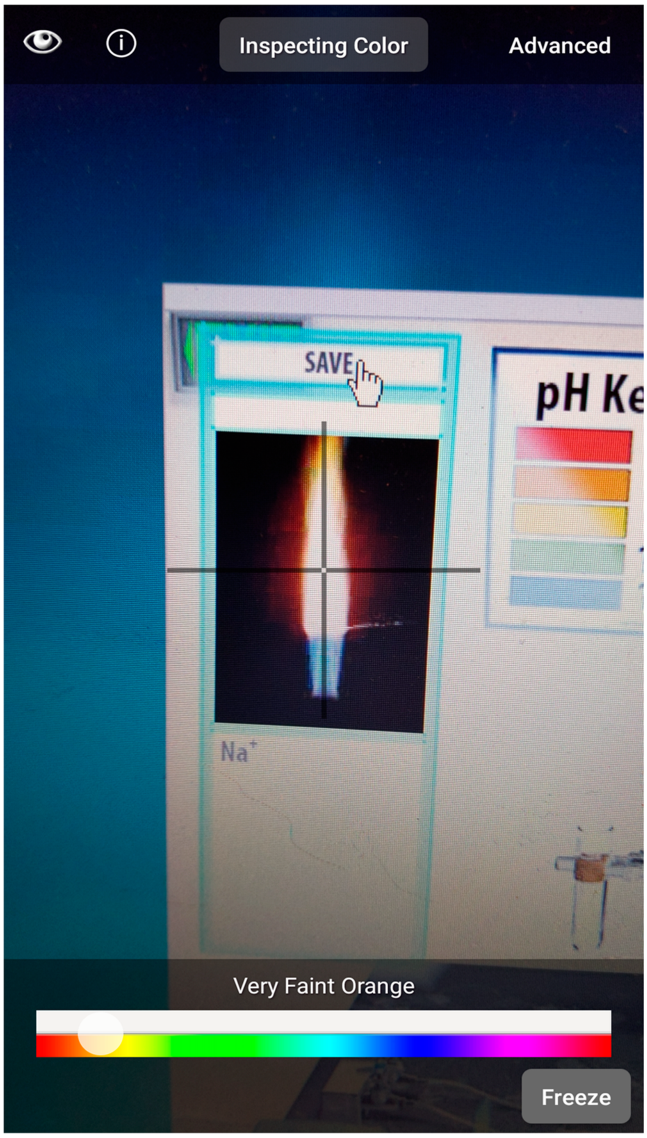

Figure 1. Screen capture from the Beyond Labz Flame Tests simulation using the Color Blind Pal app. The target is placed on the screen showing sodium metal burning, and the text readout of the color is "Very Faint Orange". Color Blind Pal printed with permission from Color Blind Pal, https://colorblindpal.com/. Copyright 2020 Vincent Fiorentini. Beyond Labz Simulation printed with permission from Beyond Labz, https://www.beyondlabz.com/. Copyright 2019 Beyond Labz.

■ INCORPORATION OF THE COLOR BLIND PAL APP INTO BEYOND LABZ EXPERIMENTS

We integrated the Color Blind Pal app into the following laboratories: flame tests and emission spectra, titrations, and precipitation reactions as shown in Table 1. The app helped us to adjust our instructions to be accessible to students while also anticipating points of confusion that could occur around color-based observations. We included instructions for students to familiarize themselves with the app and specific instructions on how to use the app in the experiments. The instructions are provided in the Supporting Information.

The first experiment where we used the Color Blind Pal app was in the flame tests activity which was hosted in the Inorganic lab simulation in Beyond Labz.[25] Students were tasked with burning several metal ions such as sodium ion and copper(II) ion and observing the colors emitted. The strontium ion produces a red flame. When we observed the flame through the "simulate deuteranopia" (red−green color-vision deficiency) function in the app, the flame looked gray instead of orange. We directed students with color-vision deficiency to use the Color Blind Pal app to view the flames as shown in Figure 1. The app allowed students to view the simulation and provided a text readout of the color underneath the target in the app screen. We received the following feedback from a student who used the app:

> *The only thing that is kind of difficult is obviously the flame does not stay one* ***color*** *so when you look through the* ***color blind*** *pal app the* ***color*** *names are kind of all over the place but for most of them it stayed on one* ***color*** *more than any other and that is the one that I went with.*

From this feedback, we saw that the app was working as intended as we wanted all students to discern which color to record based on the longest lasting color presentation.

The second activity was in the Quantum lab in Beyond Labz and was focused on interpreting atomic spectra. The activity required that students read atomic emission spectra to tell which colors on the visual spectrum were represented and then use those wavelengths to calculate the energy emitted by excited samples of hydrogen, helium, and neon. To determine the colors on the emission spectra, students with color-vision deficiency needed to use the Color Blind Pal app to capture the screen. Feedback from teaching assistants indicated that students struggled to use the app because the lines on the spectrum were very thin and placing the target on them was difficult. We learned that we needed to include directions to use the "Freeze" function for this lab. These challenges were addressed in the 2021 iteration of the course and when we incorporated the app into the remaining activities.

The second experiment where the Color Blind Pal app was implemented was Precipitation Reactions in the Inorganic laboratory in Beyond Labz.[25] Students mixed aqueous ionic compounds, determined whether solid precipitates formed, and observed the precipitate color. Using the "simulate tritanopia" setting of the Color Blind Pal app, we anticipated that students with tritanopia (blue−yellow color-vision deficiency) might struggle with making color observations about the copper carbonate precipitate formed by copper (II) ion and sodium carbonate shown in Figure 2. Using the app, students could take a screen capture of the precipitates formed in the double displacement reactions to obtain accurate color data.

The third experiment where we used the Color Blind Pal app was in Titrations hosted in the Titrations simulation in Beyond Labz;[25] students were introduced to colorimetric titrations with a preview of potentiometric titrations and titration curves. Students utilized phenolphthalein and bromocresol green to indicate the end point in a strong acid/strong base titration with aqueous solutions of sodium hydroxide and hydrochloric acid. These indicators change from clear to pink and yellow to blue, respectively, when solutions change from acidic to basic. By using the app to simulate the most common color-vision deficiency,[14] deuteranopia (red-green color-vision deficiency), we found that students would need to rely on the Color Blind Pal app for the titration with phenolphthalein indicator. Given these indicators, we directed students to hold their phone camera up to the screen and direct it at the beaker containing the hydrochloric acid as shown in Figure 3. Students could then monitor the color change via the text readout of the color in the app. In the portion of the lab where students utilized bromocresol green indicator, we asked students to collect both color observations and pH data. Combining these methods in one experiment allowed students to compare potentiometric and colorimetric methods. General chemistry laboratory curricula often present potentiometric and colorimetric titrations separately. By combining these observation methods, students could triangulate the equivalence point via pH and a color observation.

TAKING A MOMENT TO REFLECT ON ABILITY IN GENERAL CHEMISTRY LABORATORY CURRICULA

Many institutions have returned to in-person laboratory instruction or perhaps a hybridized curriculum. Rather than return to the same in-person laboratory curriculum used prior to the pandemic, instructors have the opportunity to reflect on, develop, and improve curricula.[27] Moving forward there are many opportunities to redesign curricula to support the access to and participation of a more diverse population of students through principles of universal design for learning.[5,28] Instructors can develop and implement multiple ways to ensure the accessibility of experiments and multiple ways for students to collect data.[29] Researchers have shown that incorporating multisensory approaches to teaching chemistry are useful for all learners.[30] Furthermore, use of simulations and multimedia

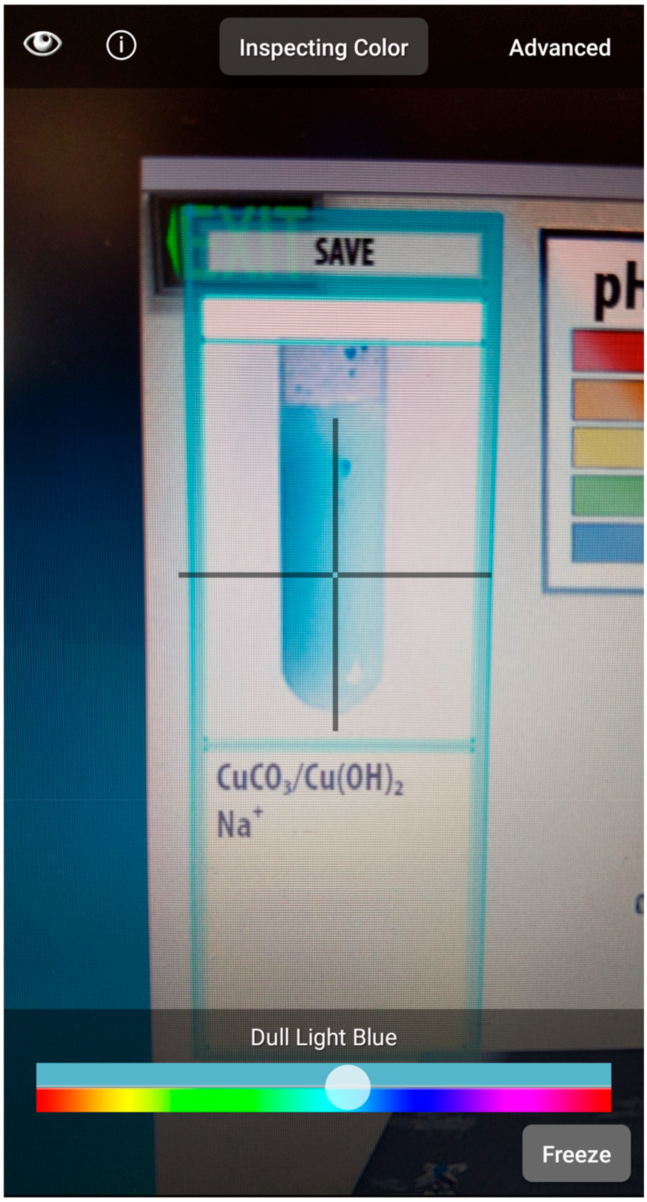

Figure 2. Screenshot of the screen capture from the Beyond Labz Precipitation Reactions simulation using the Color Blind Pal app. The target is placed on the screen showing sodium metal burning. Color Blind Pal printed with permission from Color Blind Pal, https://colorblindpal.com/. Copyright 2020 Vincent Fiorentini. Beyond Labz Simulation printed with permission from Beyond Labz, https://www.beyondlabz.com/. Copyright 2019 Beyond Labz.

can support students' access to chemical concepts through multiple modes when integrated into courses.[28−31]

Incorporating a smartphone app into our curricula was an easy way to increase the accessibility of our curriculum. We reflected on how the app allowed us to take on the perspective of students with color-vision deficiency. Using the app called into question what it means to make observations in the online chemistry lab. For instance, we needed to consider whether students who perceive color differently from the normative population are still seen to be making valid observations in chemistry.[32] In our view, student observations are valid, so we needed to consider how multiple modes of data might be offered for students to draw conclusions from. These concepts are supported by the use of universal design for learning (UDL).[28,32−36]

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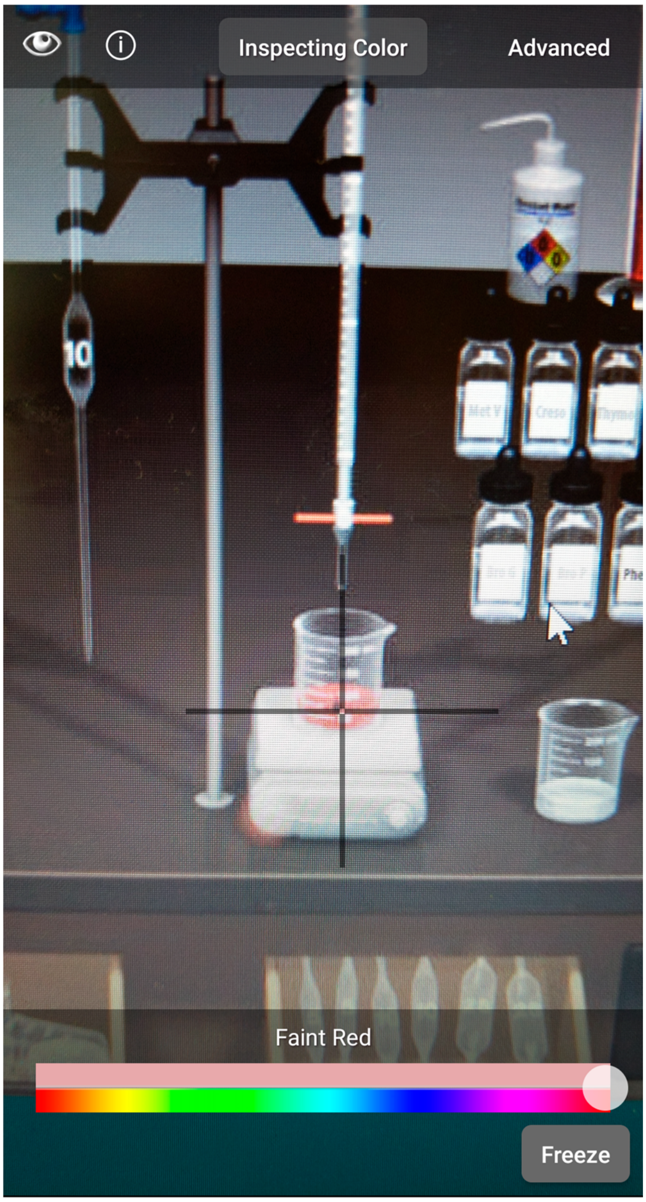

Figure 3. Image captured using the Color Blind Pal app captured in the Titrations lab in Beyond Labz. The target is placed over the beaker containing HCl and phenolphthalein after the end point has been reached to readout the color as "Faint Red". Color Blind Pal printed with permission from Color Blind Pal, https://colorblindpal.com/. Copyright 2020 Vincent Fiorentini. Beyond Labz Simulation printed with permission from Beyond Labz, https://www.beyondlabz.com/. Copyright 2019 Beyond Labz.

Universal design for learning (UDL) supports instructors in proactively designing universally accessible materials for learning to prevent exclusion.[5,36] Rather than relying on students approaching disability services for accommodations, chemical educators can use their content expertise and anticipate student needs to design a curriculum that is accessible for all learners. The UDL framework has been used to increase accessibility and participation of students' in-person laboratory curricula to support student mental health to make the laboratory space more accessible and inclusive,[37] and to assess the accessibility of widely used curriculum materials.[38] Applying this knowledge in the online laboratory space will require that students have access to multiple means to convey chemical knowledge, multiple representations of chemical content, and strategic engagement with chemical concepts.[5,39] Using the Color Blind Pal app provides a way to address accessibility in the laboratory curriculum. While the use of assistive technologies is a small step in the direction of designing accessible online laboratory curricula, we take this experience to reconsider observations in the laboratory and consider complex instruction from a UDL perspective.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00664.

Flame tests and atomic emission spectra instructions for students (PDF)
Precipitation reactions instructions for students (PDF)
Titrations instructions for students (PDF)

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Notes

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