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Laboratory Experiment

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Using Project-Based Learning To Design, Build, and Test Student-Made Photometer by Measuring the Unknown Concentration of Colored Substances

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Supporting Information

ABSTRACT: Students learned the principles and practice of photometry through project-based learning. They addressed the challenge of measuring the unknown concentration of a colored substance using a photometer they were required to design, build, and test. Then, they used that instrument to carry out the experiment and fulfill the challenge. A photometer was designed and built by students consisting of a green laser pointer as the light source and a lux meter as the detector and readout. Using this photometer students have determined the concentration of the unknown sample of $KMnO_4$ solutions. The concentration of this sample solution was calculated to be $(4.62 \pm 0.06) \times 10^{-4}$ M; this value agrees within 6% of the expected value from the measurement using the commercial spectrophotometer which was calculated to be $(4.96 \pm 0.005) \times 10^{-4}$ M. The experiments fit well into an analytical chemistry course and take a standard (1 h) lab period. This project has facilitated improved student understanding of the photometry concepts and increased the creative problem-solving. In general, the students' response to this laboratory was positive.

KEYWORDS: *Upper-Division Undergraduate, Analytical Chemistry, Laboratory Instruction, Hands-On Learning/Manipulatives, Inquiry-Based/Discovery Learning, Laboratory Equipment/Apparatus, Quantitative Analysis, Spectroscopy, UV−Vis Spectroscopy*

Photometric analysis is a topic studied in analytical chemistry lectures. Photometry is a spectroscopic analysis that measures the quantity of light absorbed by a compound from a source of visible light radiation.[1,2] A common task in chemistry is to quantify the concentration of an absorbing analyte using Beer's law. Therefore, students should understand how the phenomenon of light absorption occurs during the measurement.

In undergraduate experiments, it is usual to use sophisticated, commercial photometers. Laboratory work is taught via expository "recipe-style" laboratories, so students experience a predetermined outcome.[3] The use of this instrument prevents the students from observing all of the components; therefore, they perceive it as a "black box".[4−8] The commercial instrumentation has become so sophisticated that students have to accept that instruments work in ways beyond their understanding or caring. Everything is so encapsulated that knowledge of how things work cannot and do not need be obtained.[9] This limits the use of the photometer as a learning tool when trying to convey fundamental concepts.[7] As a result, students do not acquire a deep understanding of the experimental design, working principles of the equipment, relationship between the concepts and the observation result, and application of the concepts of chemistry and physics.[8,10,11] Commercial photometers are quite expensive and often constrain the teaching of chemistry.[8] Lab work using this model emphasizes the process of manipulating the equipment rather than understanding ideas.[12] If there are unworkable components in the photometers, students may not be able to look for alternatives, especially if there is a power outage, leaving the instrument inoperable. Students are not challenged to solve the problem creatively if such an incident occurs, whereas students should be trained to think creatively, to design, to analyze, to synthesize, and to develop awareness of the uncertainty of the measurement through laboratory practice.[13] Given these expectations, it is necessary for students

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to conduct an experiment with a photometer which is more appropriate for learning.

Several authors have described how to build simple and inexpensive absorption spectrophotometers, colorimeters, fluorimeters, and photometers.[8,14−19] Those instruments have simple designs generally, but their construction is often quite complicated, like requiring the use of light emitting diodes, compact discs, light-dependent resistors, photodiode detectors,[20] and either LabVIEW or a microcontroller.[19] Some authors have reported the use of a digital camera in a spectrophotometric analysis,[1,7,18,21−23] and a cell phone camera in spectrophotometric,[9,20,22−24] colorimetric,[21,24−28] and fluorescence analysis.[29] These experiments were simplified by the elimination of the need for a photodetector. By using a cell phone as a detector, the students can observe the color of light absorbed in the cell phone image directly, and compare it to the color of the solution. These experiments allow the students to explore the process of light absorption by a sample, which is the basic principle in absorption photometry.[9,20] However, because these experiments require a quite sophisticated analysis of digital photos, these experiments involve drawbacks for those looking for a simplified approach and make the quantitative analysis become more complicated.

In this article, we describe an experiment using a photometer built by the students which is a product of creative problem-solving as the result of an 11 week project-based laboratory. In this project, students solve the problems in determining the concentration of a colored substance by designing and building a photometer. In the globalization era, the contemporary job market demands graduates who are able to work in an ill-defined and ever-changing environment, facing nonroutine and abstract work, taking decisions and responsibility, and working in teams.[30] Therefore, students need a number of higher-level thinking skills, including problem-solving skills. The national expert analysis and commentary on the state of education have referred to the need to develop the problem solver. Therefore, the important role of an educator is to help students become problem solvers.[31]

The pedagogical concept of project-based learning is different from traditional learning in terms of trying to develop students into active learners who actively acquire the necessary knowledge to resolve the problems that appear in the project, rather than passive learners who are always receiving knowledge.[32] Project-based learning (PBL) through authentic issues allows students to engage in designing, problem-solving, decision-making, providing the opportunity to work relatively independently for longer periods of time, and producing a tangible product.[33,34] PBL grew out from the progressive education movement and reformation of constructivism science education since 1908. Dewey and other progressive educators laid the curricular and psychological foundation for PBL, which the core values are "child-centered learning", "learning by doing", and "applying school teaching at home". This model was further strengthened by the work of constructivists like Piaget and Vygotsky.[13] This learning model encourages the learners to work in teams,[35] by combining the activities of "hands-on" and "heads-in" to develop their competence through working on integrated projects.[36] PBL is a key strategy for creating independent thinkers and learners.[37] Studies have shown that this learning model improves high-level thinking skills such as creative and critical thinking skills, and problem-solving.[13,38−42] To obtain these benefits, PBL has been applied to the photometer topic.

Through PBL, students have designed and built a simple and inexpensive photometer which consists of a green laser pointer as the light source and a lux meter as the detector and readout. Students use potassium permanganate ($KMnO_4$) solution as the sample to be measured on the basis of its relevance to the wavelength of the green laser pointer. The difference between similar plans for previous homemade photometers[11,19] and this activity is that the choice of components was not mandated, but initiated by students. This experiment allows students to observe the phenomenon of light absorption by the sample without using the interface system and either LabVIEW or a microcontroller.[19] We have found that this practice model makes upper-level undergraduates excited and interested, and they developed a greater understanding of the concept. They were intrigued to see if they could design and build a photometer that functioned like a commercial device.

■ THE PROJECT ACTIVITY

There are five essential features of PBL. These are (a) an authentic question or problem which drives the activities and organize concepts and principles; (b) the inquiry community between students, teachers, and members of society as they collaborate about the question or problem; (c) the use of cognitive tools; (d) student involvement in investigations; and (e) a series of artifacts or products, that address the question/problem.[43]

Students designed and built a photometer for 11 weeks through six model stages for project-based instruction,[44] without a prelab assignment. The stages consist of orientation, identifying and defining a project, planning a project, implementing a project, documenting and reporting project findings, and evaluating and taking action. Most of the students' project was performed outside of class time. Students were provided with a worksheet to guide their project. More information about the worksheet can be found in the Supporting Information. The students worked in groups of six, and photometer projects were performed by two groups. During the project, students consulted with the lecturer regularly related to the project plan, the progress of the project, and the project's constraints. The lecturer's role was to facilitate, to advise, to guide, to monitor, and to mentor the students.[44] Questions were given as assistance to guide students to find several alternative solutions. Students were supported by discussions related to the formulation of the problems, their design, encouragement to construct the apparatus after the design was approved, and tests of their own photometer.

The orientation stage was carried out in the classroom in the first week; at this stage, the students paid attention to the explanation of the learning objectives of the project, importance of collaboration, importance of information sharing, security issues, and expected responsibilities and roles. Students also discussed how they should communicate with each other, and how their learning will be assessed. In terms of identifying and defining a project stage, students read the problem illustration about the constraints in the practice of using a photometer. This is a consequence of the first feature of PBL. They were given a challenge with the following problem: "What should you do in order to determine the concentration of a colored compound solution without using a commercial photometer?" Then, they identify the problems.

A project planning stage is done outside of class for 4 weeks. According to the guidelines in the worksheet, students have to search and learn knowledge related to the problem from various

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J. Chem. Educ. XXXX, XXX, XXX−XXX

sources at this stage, such as books, articles, and the Internet. After that, they report the results and discuss it with the lecturer. The students were also given tasks to formulate: problems based on the problem illustration, purposes of the project, importance of the project, a detailed list of the apparatus and the materials, procedures' description of the project implementation,[44] and a design of the apparatus. After completing these tasks, the students discuss it with the lecturer. Then, they improve the tasks according to the lecturers' direction. The lecturers documented these tasks as artifacts, which are the learning outcome of PBL.

To detail a list of the apparatus components, students look for various alternative replacement tools for the light source, a monochromator, and a detector which is the correct concept and is more economical. From the interview, it was revealed that searching for alternative replacement tools is the most difficult activity for students. It is represented by the statements of these two students:

Student 1: "I am very confused, looking for a replacement tool seems almost impossible and maybe it cannot be modified."

Student 2: "I didn't have any idea what components that can be modified from the photometer."

In order to assist the students, the lecturer provides scaffolding by giving directives questions. For example:

Question 1: "What is the function of radiation sources in photometer?" Question 1: "How is the working principle of the radiation source in photometer?"

Question 3: "Are there any tools that have similarity in function and working principles with the radiation source?"

The discussion illustrates the occurrence of the community of inquiry between students and lecturer; as when they were collaborating about the problem, students were actively involved in the investigation.

Through Internet searching, alternative sources of radiation that were initiated by students included a tungsten lamp, a flashlight, a white light emitting diode (LED), a single-wavelength LED, and a laser pointer. From those alternative replacement tools, the students have determined a one piece replacement tool for each of the light source, the monochromator, and the detector. As a source of radiation, the students have selected a green laser pointer. According to the student, a green laser pointer was chosen for monochromatic rays because it has a wavelength of 532 nm, so it does not require a monochromator. A single-wavelength LED was not selected by students because its rays spread out, while the green laser pointer rays is focused and narrow, so it does not require a slit. As an alternative for the detector, the tools initiated by students were a solar panel, lux meter, webcam, and photocell. The detector selected by the students was the lux meter. The reason is because the lux meter was more practical and it can serve as a detector and readout. In addition, they have become familiar with the lux meter as a device to measure light intensity as they have used it in practical general biology.

The problem that appeared was to determine appropriate compound to be measured. In determining the sample, students applied their previous knowledge about the relationship between colors and the complementary colors. During the discussion, students reported their findings from the Internet that, through the images of the color and the complementary color, the students obtained the information that the complementary color of purple was green. Purple colors absorb green radiation with a wavelength of about 530 nm. They recognized that the purple compound was potassium permanganate $KMnO_4$ solution. They also obtained the information that the maximum absorbance of the $KMnO_4$ solution was 525 nm. The lecturer also confirmed that the absorbance range of this solution is 507−545 nm.[45] On the basis of the wavelength that is emitted by the green laser pointer, students discovered that the wavelength of the green laser pointer corresponds to the wavelength range absorbed by $KMnO_4$ solution. Therefore, the students assigned $KMnO_4$ as the sample solution.

After they finished determining tools, materials, and the sample, students drew a photometer design. They finished the drawing with a detailed description of the working principles and each of the components' functions, and an explanation of the work process flow. They discussed the drawing with the lecturer, and then improved it.

Implementing the project stage was done outside of class for 3 weeks. At this stage, students prepared equipment and materials needed according to the project plan and the photometer design and developed procedures to practice. Furthermore, students constructed and tested the apparatus. The process of constructing a photometer is not a one-time process. Through discussions, watching the videos of photometer construction by students, and interview results, it was revealed that, at first, the photometer was packed using a cardboard box. In the beginning, students determined the concentration for measurements using $KMnO_4$ solution without considering the concentration and the distances; however, the green laser pointer intensity was not readable by the lux meters. Then, they discuss with the lecturer about the obstacles. The advice given by the lecturer was that the students must determine the appropriate concentration range and distance for the measurement. After discussion with the lecturer, the students repeated the experiment with the solution concentration of 0.02 M, the distance from the green laser pointer to the sample holder of 5 cm, and the distance from the sample holder to the lux meter of 10 cm; however, it was still not readable. After looking for the information from the Internet, the students obtained the concentration range for the measurement that is 0.0001−0.0010 M. Then, they repeated the experiment using $KMnO_4$ solution with this concentration range using the same distance; the result was that the green laser pointer intensity can be read by the lux meter. Finally, they packed the photometer in a cardboard box. Further information can be found in the photometer design section. On the other hand, procedures have been provided in traditional experiments, so there will be no obstacles in doing it, but the students were not trained to solve the problems. At this stage, students also developed the experimental procedure. More information can be found in experimental details. Then, the students conducted an experiment. They had a 1 h lab period to determine the $KMnO_4$ concentration. They recorded and processed the observed data, and constructed a standard curve. Thus, at this stage, the artifacts that have been produced by students were data and a photometer as the product of PBL.

Documenting and reporting the project findings stage was done for 3 weeks. The first 2 weeks were spent outside the classroom, and students prepared for the project's report. In the third week, they presented the project findings in the classroom. Students complained about the lack of time for this project. Moreover, a delay at the online delivery of tool was also an obstacle because the trial process must be delayed too.

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J. Chem. Educ. XXXX, XXX, XXX−XXX

As a consequence, students' activities become overloaded at the end of the semester.

The implementation of this project was very much supported by the use of cognitive tools such as computers and telecommunications. By using this technology, the environment is more authentic to the students because it provides access to data and information and expands interaction and collaboration with others via a network.[43]

During the project, students' creative problem-solving was assessed using the performance assessment instrument. Performance assessment that has been done consists of the process of performance assessment for planning and designing the photometer (presented in Table 2, top), and the product performance assessment of a photometer that has been built by students (presented in Table 2, bottom). This assessment was appropriate to be applied to PBL, in addition to the models such as case-based assessment, self- and peer-assessment, and portfolio assessment.[30] The assessment of these artifacts was conducted by using a rubric and scoring. The performance assessment instrument was arranged by the highest grading rubric score being 3 and the lowest being 1.[13] Further information about the performance assessment instrument can be found in the Supporting Information. This performance assessment was an assessment for learning. Students reported the artifacts of their performance and discussed these with the lecturer. The lecturer evaluated and provided feedback on the artifacts so that students could learn from that evaluation and improve performance during the project.

■ PHOTOMETER DESIGN

The photometer constructed by the students consists of a green laser pointer as the light source, a glass sample holder, and a lux meter as the detector and readout. These components are packed into a cardboard box of 50 cm × 20 cm × 20 cm (Figure 1). The distance from the green laser pointer to the sample holder is 5 cm, and that from the sample holder to the lux meter is 10 cm. The photometer can be set up in approximately 3−5 min and costs less than $35.

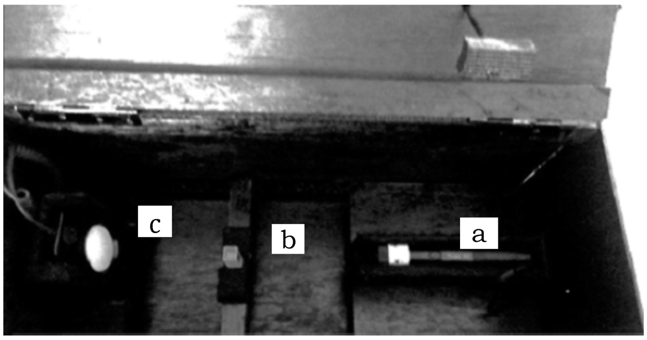

Figure 1. Photograph of the photometer apparatus: (a) green laser pointer, (b) sample holder, (c) lux meter.

The laser pointer used in the photometer is a green laser pointer charge 303 (Figure 2). This tool generates a bright green laser beam with a wavelength of 532 nm. The laser pointer uses 1 rechargeable 18650 lithium battery.[46]

A lux meter is a tool used to measure the intensity of light hitting or passing through a surface.[47] The lux meter used in this photometer is the Lutron LX-101 (Figure 3). The lux meter measures lumen/m^2, or candela steradian/m^2 (solid angle of 1 rad).

Figure 2. Photograph of a green laser pointer charge 303 with the following specifications: surface treatment, black anodized; battery, lithium 18650; max output, <3 W; working voltage, dc 3.7 V.

Figure 3. Photograph of a lux meter lutron LX-101. Specifications follow: ranges, 0−50,000 lux, three ranges; zero adjustment, internal adjustment; sampling time, 0.4 s; sensor structure, the exclusive photodiode and color correction filter; operating temperature, 0−50 °C; power supply, dc 9 V battery, 006P, MN1604 (PP3), or equivalent; power consumption, approximately dc 2 mA.

A sample holder support has been made by students, in order to shift and to adjusted the distance from the green laser pointer to the sample holder, and from the sample holder to the lux meter, to produce the largest reading. In addition, the green laser pointer and lux meter were not permanently installed and can be removed and replaced as needed. The cost of this student-made photometer (a common glass sample holder is not included) can be seen in Table 1, ~$35 total.

■ EXPERIMENTAL DETAILS

This experiment required 1 h of lab time, and the students worked in groups of six. The students began the experiment by preparing six standard $KMnO_4$ solutions (0.0001−0.0010 M). Then, they set up the photometer by mounting the green laser pointer, sample holder, and lux meter to allow the light to pass

Table 1. Description of the Components Used To Build the Photometer

Component	Model Number	Price/$
A lux meter	Lutron LX-101	10
A green laser pointer	Charge 303	23
A glass sample holder		
wood plank		2

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J. Chem. Educ. XXXX, XXX, XXX−XXX

through the sample solution which they want to measure, as shown in Figure 4.

Figure 4. Photograph of the measurement of the transmitted light.

The experimental procedure developed by the students can be found in the Supporting Information. Students measured the transmitted intensity for water, the six standard solutions of $KMnO_4$, and sample prepared by the instructor. Students recorded the intensity measured with water as the intensity of the incident ray I_o, and the standard and sample solutions as the intensity of the transmitted ray I. They used these values to calculate transmittance using the equation

$$T = \frac{I}{I_o}$$

Then the absorbance was calculated from the transmittance using the equation

$$A = -\log T$$

where T = transmittance, I = transmitted light intensity, I_o = incident light intensity, and A = absorbance.

This procedure was done three times for each standard solution and the unknown sample. Finally, students constructed a calibration curve with an equation (Beer's law) and determined the concentration of $KMnO_4$ in the solution prepared by the instructor, using a calibration curve equation. For comparison, the instructor measured the standard solutions and the prepared sample using a commercial HSP 788 UV−vis spectrophotometer at λ (wavelength) = 525 nm which is the wavelength of maximum absorbance for $KMnO_4$.

HAZARDS

The beam of the green laser pointer can cause eye damage. Therefore, do not point the beam toward a person's head or eyes, so as to prevent the beam from entering their eyes. Potassium permanganate is a strong oxidant and will discolor skin and stain the clothes.

RESULTS AND DISCUSSION

Performance Assessment

As shown in Table 2, the value of the performance assessment indicates that, overall, students have developed creative problem-solving skills during the project. They have written the problem formulation and initiated the alternative replacement of the commercial photometer components: designing, constructing, testing tools, and evaluating. They also have produced tangible products as a manifestation of creative problem-solving in the project-based practice.

Table 2. Comparative Performance Assessment Results for the Creative Problem-Solving Project

	Process Performance	
	Item Indication of Creative Problem-Solving Process	Score[a,b]
1	Based on the problem, students write the relevant problem formulation.	87, 88
2	Based on the problem, students write the varied problem formulations.	81, 82
3	Based on the problem, students write the relevant ideas' formulation of the project's purpose.	90, 91
4	Based on the problem, the students write the relevant ideas' formulation of a project's importance.	87, 88
5	Students described the apparatus modification procedure; concepts are correct and relevant.	69, 70
6	Students detail a list of the apparatus' materials with adequate amounts, and relevant materials.	78, 79
7	Students draw a design of the apparatus, using correct concepts and specifying less-costly materials than a commercial apparatus.	87, 88
8	Students describe the function of each component of the apparatus.	93, 94
9	Students describe the working principle of each component of the apparatus.	90, 91
10	Students describe the operating principles of the apparatus on the design.	90, 91
	Product Performance	
	Item Indication of Creative Problem-Solving Product	Score[a,c]
11	Students replace the radiation source with one that is less-costly than a commercial apparatus.	100, 100
12	Students replace the detector system with one that is less-costly than a commercial apparatus.	100, 100
13	Students assemble the apparatus in a compact and attractive manner.	81, 82
14	Students test to prove that the apparatus can function similarly to a commercial apparatus.	81, 82
15	Students test to prove that the apparatus design is easy to build and use.	81, 82

[a]Scores could range from 0 to 100. [b]N = 12. [c]Assessments based on photometer product.

Photometer Performace

A standard curve that has been made by using data from the student-built photometer created by one group is presented in Figure 5. The figure also contains data from the instructors, obtained by using a commercial HSP 788 UV−vis spectrophotometer at λ = 525 nm.

As seen in Figure 5, the plots of absorbance versus concentration are approximately linear for both curves over the entire investigated concentration range (0.0001−0.0010 M), although there is a larger measurement of deviation for the student-built photometer. By using the most appropriate line equation, the concentration of the unknown sample measured by using the student-built photometer was calculated to be $(4.62 \pm 0.06) \times 10^{-4}$ M; this value agrees to within 6% of the expected value from the measurement using the commercial spectrophotometer which was calculated to be $(4.96 \pm 0.005) \times 10^{-4}$ M. In this experiment, students obtained an experience reflecting that experimental data do not always follow Beer's law; some of them deviate positively and negatively. Conversely, students in a traditional laboratory are usually required to follow a recipe in order to arrive at a predetermined conclusion. So, they only spend more time determining whether or not they obtained the correct results rather than thinking about planning and organizing the experiment.[3]

During the project, students found that the distances and concentrations of the solution greatly affect the measurement.

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J. Chem. Educ. XXXX, XXX, XXX−XXX

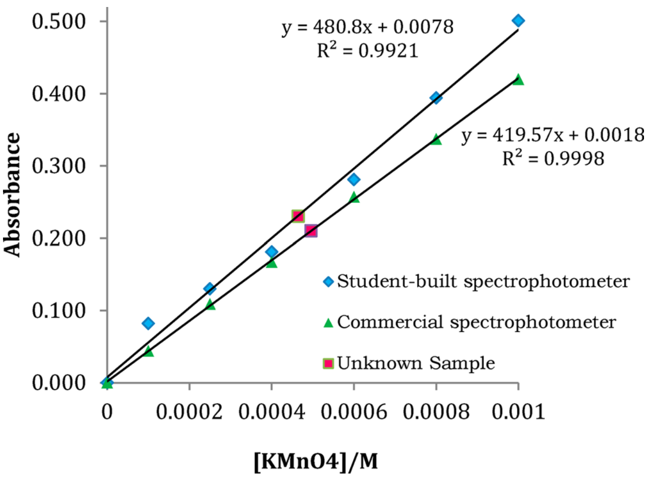

Figure 5. Calibration curve for a series of standard potassium permanganate solutions from two types of instruments. All measurements were made with a 1 cm path cell. Deviation of the mean (DM) for the student-built photometer = 0.0045; DM for the commercial HSP 788 UV−vis spectrophotometer = 0.0009.

Although they have theoretically learned that the distance is affecting the measurement, it is a new and valuable experience for them. They reported that, for a concentration of 0.02 M, the transmission intensity of the green laser pointer was not measurable. Here is the student's statement in the discussion: "We have learned that Beer's law applies in dilute solutions, but we do not know how much the concentration. Therefore, we just try it with a concentration of 0.02 M." Perhaps at high concentrations almost all the light is absorbed by the sample's molecules, causing the remaining light to be insufficient for quantitative measurement. By varying the concentration of the solution, students proved that Beer's law applies to dilute solutions[48] within a specific range. When they conducted the experiment, they observed that there is a difference of transmission intensity between the water and the standard $KMnO_4$ solution; they also explored the process of light absorption and were surprised that the absorption is precisely measured by the difference of light intensity transmitted by the solution and the water. Thus, a green laser pointer and lux meter were chosen not only because of their simplicity and low cost but also to provide an opportunity to teach the process of light absorption by a sample, which is the basic principle in photometry absorption.

The main source of error in the experiment is the scattered light from the room. The scattered light can cause a deviation from linearity on the calibration curve. The measurement and instrument likely could be improved by the inclusion of a dark reading by placing a blackened cuvette and making a measurement with a green laser pointer on.

Through this project, the students gain valuable experience on how to plan the investigation, take measurements, solve the problem creatively, analyze the results, and appreciate the measurement uncertainty.[13]

Students' Response

In terms of obtaining feedback, we collect the students' responses to these practice models through questionnaires and interviews. As shown in Figure 6, the questionnaire responses indicate that, overall, students responded well to the project model in this lab, and most of the students said that they found the laboratory to be very interesting, beneficial, enjoyable, exciting, and challenging. They said, "wow amazing", we can build a photometer that functions the same as commercial tools. In response to the question of "What did you think about this project?", most of the students answered, "We have a better understanding of the photometry concept because we have read more and had to find information to finish our project. Through this practice model, we understand that the basic simplified instrument is similar in function and working principles, and more become confidence."

■ CONCLUSIONS

Through project-based practice, students have successfully designed and constructed a simple photometer. The photometer is constructed easily and can be used to measure the concentration of $KMnO_4$ solution. The student-built photometer has the following benefits compared to the commercial system: low cost, ease of construction and use, and greater student understanding of photometry concepts. This project has facilitated the improvement of students' creative problem-solving skill.

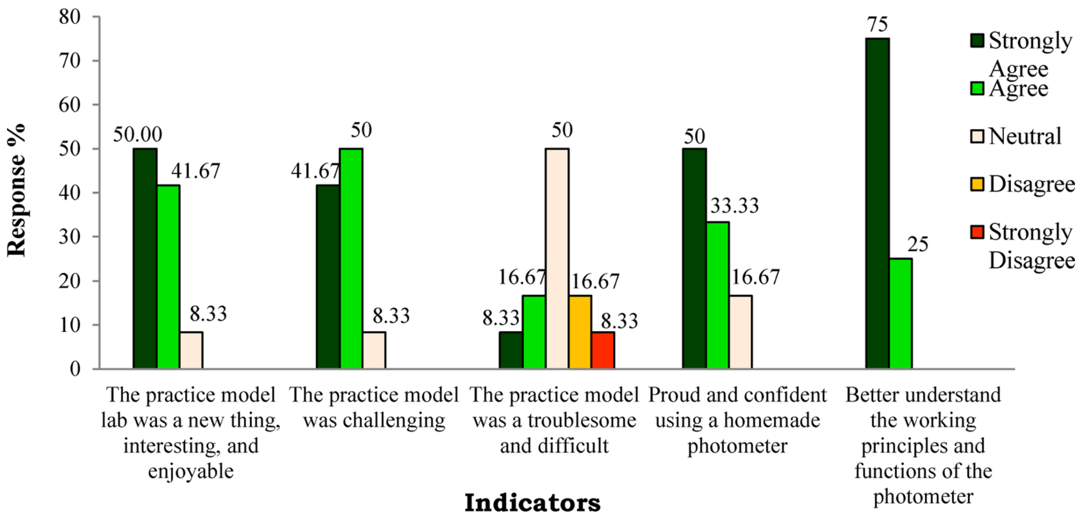

Figure 6. Graph of student responses to the model of project-based practice (number of respondents = 12).

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J. Chem. Educ. XXXX, XXX, XXX−XXX

Generally, students' response to this laboratory was positive, with the main criticism being a lack of time to do the project. The criticism was also addressed regarding the use of green laser pointer which has a relatively large power (<3 W). As the result of this feedback, we are improving the performance of the photometer for project implementation in the future.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

These materials are available via the Internet at The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.7b00254.

Typical data (PDF, DOCX)
Interview guidelines (PDF, DOCX)
Experimental procedure prepared by the students (PDF, DOCX)
Student worksheets (PDF, DOCX)
Performance assessment instrument (PDF, DOCX)
Student questionnaire (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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