Mass is Better than Light: Students' Perception of Using Spectrophotometry and Gravimetric Analysis to Determine the Formula of a Hydrate in the General Chemistry Lab

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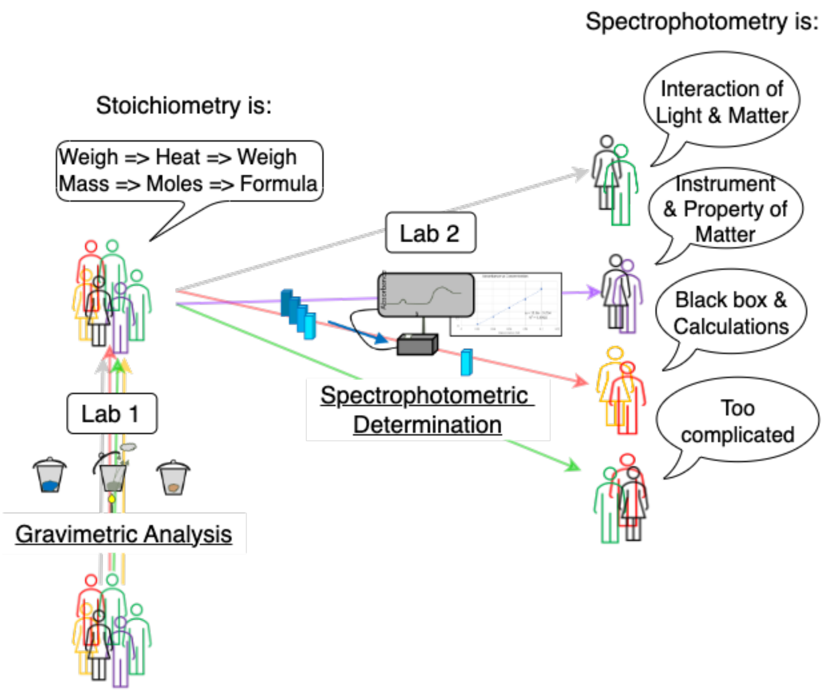
ABSTRACT

A key part of the practice of chemistry is the analysis of chemical composition, including through gravimetric analysis and spectrophotometry. However, the complexity of doing multiple calculations to obtain analytical evidence, such as that required to determine an empirical formula, presents a challenge if such analytical methods are to be understood by students and if they are to support meaningful learning about other chemical concepts and methods. In this study we investigate student use of spectrophotometry and gravimetric analysis to determine the number of water molecules in hydrates of copper (II) salts, a method previously described by Barlag and Nyasulu. Using phenomenography to analyze students reports through the lens of meaningful learning we identified four distinct perceptions and, within them, information of how students make sense of the complex analytical steps involved in the experiment. We identify how meaningful learning is present where students recognized that spectrophotometry was based on light-matter interactions (cognitive,) was faster and more accurate (psychomotor), and allowed students to express confidence in the process and their results (affective). However, it is also the case that meaningful learning was compromised where students had trouble conceptualizing spectrophotometry, saw it as a set of disconnected steps, and where they saw absorbance as a computer-generated value and not a property of the solution. This led to the perception that gravimetric analysis provided a more direct and understandable technique. We discuss the implications of these findings for chemistry education research (CER) and for curriculum development in the undergraduate teaching lab.

GRAPHICAL ABSTRACT



KEYWORDS

First Year Undergraduate/General, Laboratory instruction, Meaningful Learning, Phenomenography, Analytical chemistry, Gravimetric Analysis, Spectrophotometry, Chemical Education Research, hydrates.

INTRODUCTION

The teaching laboratory is a "complex learning environment" in which students must integrate knowledge, skills, and attitudes.[1] Student learning involves constructing, verifying, and applying chemistry concepts by means of procedures, equipment, and chemicals that have their own discipline-specific meanings. This swirl of activity happens in a time-constrained, performance-oriented, and content-heavy setting[2] in which students and faculty often hold very different goals.[3–5] Yet we often know little about what students are actually experiencing or learning, which led Stacy Lowery Bretz to note: "Chemists can no longer afford to believe that the importance of teaching laboratories is a truth we hold to be self-evident."[6] There are important frameworks about how to structure the goals and methods of laboratory work, some of which are accompanied by empirical work that analyzes how students perform relative to the stated chemistry content goals while other studies uncover the disconnect between students' experiences and stated learning outcomes. However, few studies have sought to directly link chemistry content goals with students' descriptions of their experiences of the laboratory.

In this study, we look at what happens in student learning in a common example of laboratory work: analysis of a sample for information on mole amounts that is used as evidence for determining an empirical formula. This builds on a two-week lab sequence adapted from a laboratory activity by Barlag and Nyasulu where students do a stoichiometry experiment using gravimetric analysis followed by spectrophotometry.[7] We qualitatively analyzed students' perceptions of the lab activity through a phenomenographic lens[8] using a meaningful learning framework.

Background

The use and understanding of spectrophotometry are critical to students' chemical literacy as it pertains to laboratory work as an interaction between matter and light[9] and as a key component of many analytical methods. Spectrophotometry involves the measurement of the absorption and transmission of light by a sample as a function of wavelength and concentration and is also important outside of chemistry, in fields such as medicine, forensics, materials science, and environmental studies[10,11] Additionally, understanding spectrophotometry allows students to explore the principles behind other analytical techniques that allow understanding of chemical properties, molecular interactions, and structure. The ACS Exams Institute, in its Anchoring Concepts Content Map, documented the importance of having undergraduate chemistry students gain both a conceptual and practical understanding of spectrophotometry and the light-matter interactions[12] and that these are the basis of a multitude of applications at every level of chemistry.[13]

While many first-year undergraduates experience learning about light and matter, these often occur in a fragmentary manner.[14,15] Typically in high school, the systematic study of light occurs in physics courses and is unrelated to matter with minimal coverage beyond electron configurations in chemistry classes. Also, high school students are unlikely to use spectrophotometers because of cost and time constraints,[16–18] and, for the students in our study group, this situation was made worse by the pandemic and online learning. There may also be issues with existing curricula standards. While the National Research Council's *A Framework for K-12 Science Education* references the "interaction of electromagnetic radiation and matter" (Disciplinary Core Idea PS4.B[19]), its application within the *Next*

Generation Science Standards (NGSS) (the basis for learning standards for the bulk of our students[20]) does not include any examples of spectrophotometry itself. The only chemistry-related reference of the interaction of light and matter is in performance expectation HS-PS4-4 that states, "Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter."[21] While some high school students might use spectrophotometers in an AP or second year chemistry course and received instruction in the interactions of light and matter at a molecular level,[22,23] these students often bypass the first semester general chemistry lab.

Chemical education researchers are beginning to consider students understanding about light-matter interactions and their misconceptions.[9,24,25] These misconceptions and fragmented understandings are exacerbated when general chemistry students have limited exposure to the use of instrumentation in chemistry[26] and the chemistry lab.[27] As most incoming students' laboratory experience is with balances, glassware, and Bunsen burners, the introduction of an instrument as complex as a spectrophotometer is likely to be met with anxiety and nervousness.[26] This is part of students' overall anxiety with the prospect of laboratory work.[28] Thus, student success in a laboratory that requires collecting and analyzing spectrophotometric data is anything but assured and the ability to link conceptual understanding with technical skill is a difficult prospect.[29]

Being dependent on technology to generate data can lead students to see the spectrophotometer as a "black box" whose inner workings are unknown to the user.[30] This contrasts to other examples of technology in the lab such as electronic balances and thermometers, which are not particularly troublesome because students have well-grounded experiences with and understanding of the relationship between the object and the property being measured.[31] The situation is likely very different with a spectrophotometer—the substance is put into a solution, the solution is transferred into cuvette that is put into a well, and light is passed through the sample and measured by a detector that is both out-of-sight and functioning with principles unknow to most students. The spectrometer produces numeric data in the form of a graph or value on the screen that is then recorded. This value—absorbance at wavelength—is not linked to a simple phenomenon. Rather, the student combines it with other measured values of absorptions at known concentrations to calculate the concentration of the substance in the solution. Then, if students are to move beyond concentration to the stoichiometrically-relevant value of moles and formula determination, the process is complex[32] and a significant distance exists between the object—the empirical formula—and its—light absorbance at a particular wavelength.

Recent articles have appeared proposing activities and projects to bridge this gap. These typically followed one of two paths. The first involves the use of spectrophotometry to determine the presence or concentration of substances of presumed interest to students—vitamin C in supplements,[29] aspirin in over-the-counter-drugs[33] and its removal from treated water,[34] caffeine in coffee beans,[35] and herbicides in soil samples.[36] The second path to help students understand the theory behind spectrophotometry involves building "homemade" spectrophotometers of various sophistication,[16,37–42] many of which were reviewed by Kovarik et al.[42] While many of these articles propose activities to make spectrophotometry understandable to students, only a few contain evidence of student learning.[29,36,43] Kovarik *et al.* note this dearth of evidence[42] and observe that authors only occasionally mention that students appeared engaged in or appreciative of the activity.

Our study seeks to look more deeply at the students' experience with spectrophotometry and how learning is occurring. We do this in part by contrasting it with their experience with a more direct (but less relevant) method: gravimetric analysis. Using the multidomain framework of meaningful learning we characterize how cognitive, psychomotor, and affective learning intersect to support or limit meaningful learning in this sequence of laboratories.

LEARNING THEORY FRAMEWORK

Novak's theory of meaningful learning and human constructivism

The lab activity and the study in this paper are structured on Novak's theory of meaningful learning. In meaningful learning, three things must be present:

1. The learner must have a cognitive structure into which the new material can be incorporated
2. The new material must be meaningful to the learner
3. The learner must choose to incorporate the new material into their cognitive framework[44,45]

These must occur within the student's experiences in the cognitive, affective, and psychomotor domains.[46,47] The cognitive learning domain involves students' mental processes of thinking, understanding, and explaining; the psychomotor domain involves students acting on and in the laboratory setting; and the affective domain involves student emotions and motivations.

In contrast to rote memorization, meaningful learning can carry over into novel situations and remain a part of a student's cognitive framework.[46] In structuring this pair of labs, (see figure 1), the first lab, gravimetric analysis of a hydrate, was chosen to build the students cognitive structure by scaffolding concepts that are crucial for success in the second lab: mass-to-mole calculations, mole ratio determination, and properties of hydrates. When they performed the same stoichiometric analysis in the spectrophotometry lab, they had previous experience that gave them context for the chemical stoichiometry problem they were trying to address. The pre-lab lecture to spectrophotometry encouraged students to consider another way to arrive at hydrate formulas. Finally, in writing their reports, students were asked to reflect on the similarities and differences between the two methods, thus incorporating light-matter interactions, absorbance to concentration, and concentration to formula into their cognitive framework. In this design, we anticipated that the requirements of meaningful learning would be met and students would perceive spectrophotometry as more meaningful.

In collecting evidence of meaningful learning, we analyzed our data through the students' expressions in the three domains of learning, explicit in Novak's Human Constructivism. While students were not specifically prompted to discuss their learning in each domain, by observing what students wrote in comparing these two experiments through the lens of meaningful learning , we operationalized the learning domains to give us insight into where meaningful learning of spectrophotometry in the laboratory was occurring.

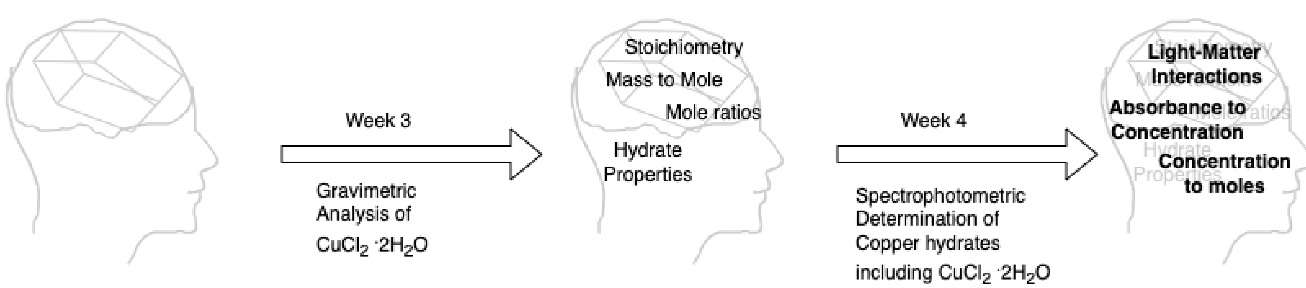


Figure 1. Cognitive model of laboratory activities showing general timeline and anticipated cognitive outcomes for the labs based on Novak's theory of meaningful learning. In week three, the students performed a heat to constant mass procedure to determine the formula of a copper (II) hydrate. In week four, they carried out their first use of spectrophotometry and molarity to determine the formula of copper (II) hydrates. The silhouettes list the expected outcomes of each activity.

METHODOLOGICAL FRAMEWORK

Phenomenography

In our work, we seek to understand students' conceptions of what they are experiencing by examining their own statements about what they are doing. To do this, we used phenomenography, which is a qualitative research approach in which the focus of the research is on the different ways that a phenomenon is experienced.[48,49] Conceptions are different ways people experience, perceive, understand, or conceptualize an aspect of the world around them.[50,51] While a phenomenographic study relies on the individuals' expressions as the data set, the focus is on the variety of conceptions and not on any one individual's conception.[50] Thus, an individual may hold more than one conception at any time.[52,53] By investigating peoples' conceptions, phenomenography takes a second-order perspective rather than the researcher's perception of the phenomenon, which is a first-order perspective.[54] A phenomenographic study produces an outcome space in which these qualitatively different ways students perceive and experience a phenomenon are described and related to each other. These varying perceptions become the categories of description that document the experiences and meaning of the phenomenon to the learner.[55] Phenomenographic methods assume there are a limited number of different ways of experiencing the phenomenon[56] and that the research can uncover these. In this study, the phenomenon is construed as doing gravimetric analysis followed by spectrophotometry to determine the formula of a hydrate in the laboratory setting (Figure 2).

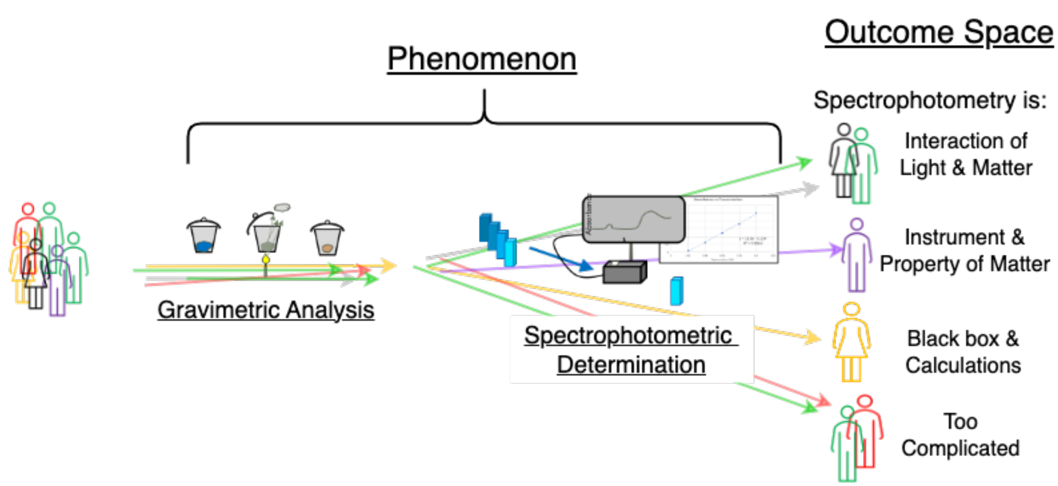


Figure 2. Graphical representation of phenomenographic study of students' perceptions of gravimetric analysis followed by spectrophotometry in determining hydrate formulas. The different colors, lengths, and starting/ending points of the arrows are purposeful to depict student variations in how they traverse the phenomenon. Student perceptions of spectrophotometry are given in the outcome space .

While phenomenographic studies can use interviews of a small number of participants, this study used a large number of written responses to open-ended prompts. This allowed us to look closely at the perceptions of a larger sample of students in order to gather a large amount of information in a relatively short time[57] and to develop a richer understanding of the phenomenon being studied.[58] A potential drawback of using written responses is that they are less detailed than interviews, and an individual's expressed conception may be incomplete.[59] On the other hand, written responses from a large group of students allows a wider range of student experiences that can be mapped into a more complete set of variations of conceptions.[60]

RESEARCH QUESTIONS

This study seeks to answer the questions:

1. What are students' perceptions of spectrophotometry in the context of the introductory chemistry lab?
2. How do students perceive the difference between the analytical techniques of gravimetric analysis and spectrophotometry.

The intent of this research is to provide empirical data on students' perceptions of spectrophotometry in the general chemistry laboratory, and to uncover the relationships which are present among these perceptions. By analyzing undergraduate chemistry students' written expressions through the lenses of meaningful learning and phenomenography, we present an outcome space that delineates students' learning and their perceptions of spectrophotometry in the laboratory setting. These perceptions are grounded in students' experience and are due to different patterns of awareness—how individuals perceive and experience different components of the phenomenon.[54,56] This provides educators with the empirical evidence needed to make informed decisions rather than "gut instinct or personal experience"[61] about curriculum design called for in reforming general chemistry[62] and to "narrow the gap between research and practice" in the teaching lab.[63]

DESCRIPTION OF LABORATORY ACTIVITY

This work was done within a general chemistry laboratory class at a large midwestern urban university serving a population with no majority ethnic or racial demographic. The laboratory is a two-credit, one-semester course taught independently of the introductory lecture course. It includes 12 labs over a 15-week semester and serves students in traditional chemistry and biochemistry tracks, as well as other STEM majors, and preprofessional tracks—including nursing, pre-pharmacy, and pre-medicine. Lab periods are three hours long, contain up to 24 students, and are led by one graduate teaching assistant (TA).

Each lab activity follows the same general format. Prior to coming to lab, students are required to watch an asynchronous lecture video by the lead instructor which covers theory, concepts, and procedures. Two optional videos are also available online: A video of the procedures and a video on completing the post-lab. Additionally, students are required to read the introductory material and procedures for the lab, prepare their lab notebooks, and complete an online quiz in the course's learning management system (LMS). At the beginning of lab, TAs give a brief lecture on safety and waste disposal and answer questions. Students then work on the lab in pairs while the TA circulates. Post-labs are completed on the LMS and include data entry, results and calculations, answers to questions, and an upload of photos of students' lab notebooks including sample calculations. The results and calculations are graded automatically with immediate feedback, and TAs grade open-ended questions and notebook uploads. Post-labs are due before the next lab.

The activity described in this study occurred in week three and four of the course in the fall of 2022 (figure 3) and in week two and week five in the spring of 2023 (see below for rationale).

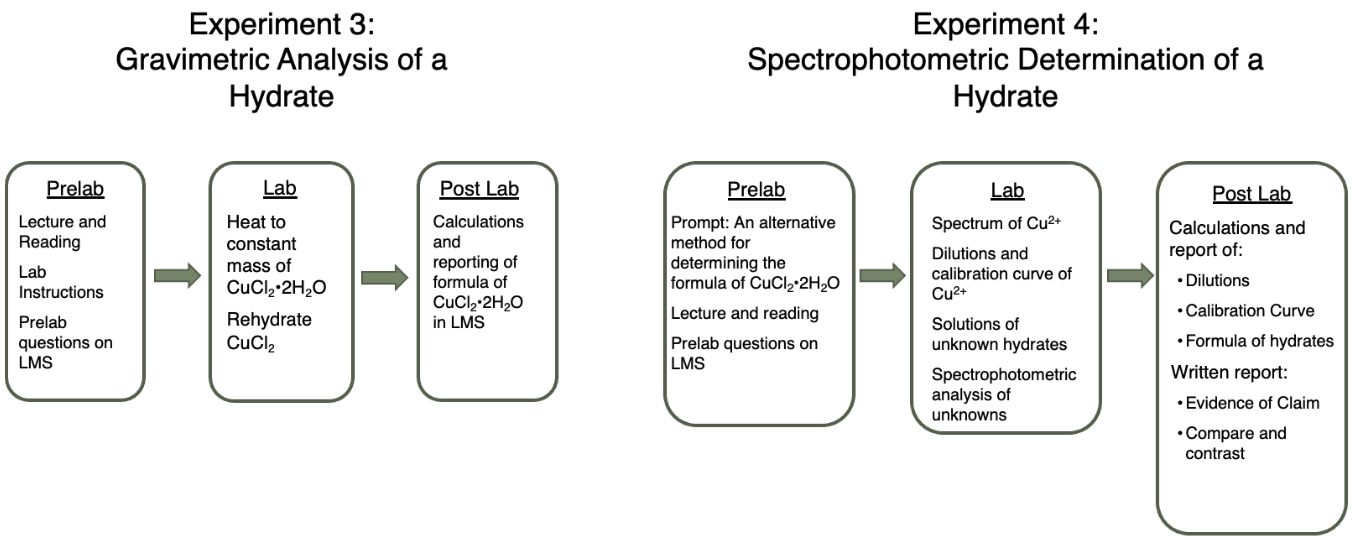


Figure 3. Task diagram of the two-week lab activity involving gravimetric analysis followed by spectrophotometry to determine the formulas of copper (II) hydrates.

Both experiments were adapted from the procedure of Barlag and Nyasulu[7] to fit within the general course structure. In gravimetric analysis, students weigh a hydrate sample before and after heating in an oven and calculate the empirical formula. In spectrophotometric determination, students use a spectrophotometer and self-made standards to produce a calibration curve that they use to determine the concentration of a solution made with a hydrate and measured for absorbance. Then using molarity and stoichiometry, they determined the formula (See supporting information for more detailed procedures). Figure 4 is a schematic diagram of the procedures necessary to get the formula of $CuCl_2 \cdot 2H_2O$ for the two labs.

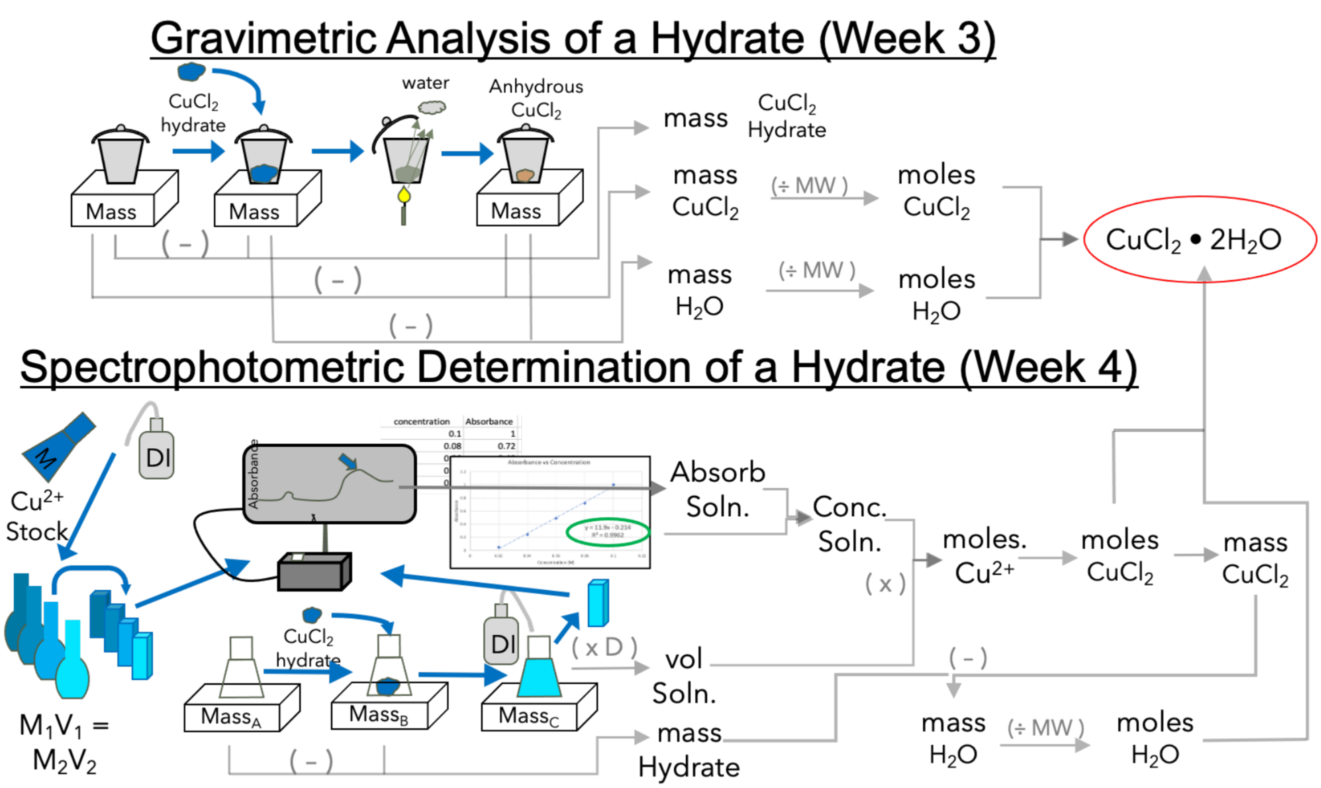


Figure 4. Schematic diagram of the processes involved in determining the formula of the hydrate $CuCl_2{\bullet}2H_2O$ in the two laboratory activities. Psychomotor processes are coded as blue arrows while cognitive processes are coded with grey arrows.

Students submitted their data, results, sample calculations and the answers to the prompts on the LMS. The prompt asked for a discussion of the results and a comparison of spectrophotometry with gravimetric analysis:

> “This week and last week, we determined formulas of hydrated copper compounds using two different methods. In paragraph format, compare and contrast these two methods and the results you obtained using these methods. Include a specific comparison of the values you got for copper (II) chloride.”

Additionally, for this lab, students submitted a written or typed report that asked them to include data tables, a results and discussion section which required an explanation of how they arrived at their formulas. This report was submitted to the LMS for grading by the TA’s.

After a preliminary analysis of student lab reports, it was apparent that students were not responding to spectrophotometry as positively as we had anticipated (see results and discussion). In response, we restructured the labs for the spring 2023 semester by moving a traditional acid-base titration lab, to provide students with experience using molarity, moles, and volume in the lab; and a gas laws lab to provide more practice with working with quantities in chemistry to the weeks between the gravimetric analysis lab and the spectrophotometric determination of hydrate lab. This sought to provide students with additional scaffolding before carrying out the spectrophotometric determination lab. We also added the following two prompts for students to answer after the spectrophotometry lab:

- In a short paragraph in your own words, explain how a spectrophotometer works.
- Describe in a paragraph how to use spectrophotometry to determine the formula of a hydrate. You do not need to include actual values in your explanation.

METHOD

Position of the researchers.

Both authors were significantly involved in the development and implementation of the activity, including adapting the procedures, producing the supporting material, and writing the assessments. The second author was instructor of record for the fall 2022 course and produced the asynchronous lectures for all the labs. The first author coordinated the TAs for the course, produced the procedure videos, recruited volunteers for the study, and anonymized and coded the data.

Data Collection

Data were collected from students who completed both the gravimetric analysis and the spectrophotometric determination of copper (II) hydrates in the fall of 2022 and consented to have their lab reports accessed through the LMS in compliance with the University's IRB (ID# 2018-1323). 280 participants of 600 enrolled students consented to have their ungraded lab reports used in the study. Of these, we randomly selected 100 reports to use in this study. Of those, 63 specifically answered the prompt to compare and contrast gravimetric analysis and spectrophotometry. These were downloaded, anonymized, and analyzed using MAXQDA 2022. Pseudonyms were given to participants data using NOAA hurricane names[64] and assigned to randomized reports irrespective of gender and ethnic identification of participants.

An additional set of 58 lab reports was collected from students from the spring of 2023 using the same criteria as the previous semester, with the intention of verifying the coding structure and the outcome space. These reports also included additional prompts to gain more data concerning student perceptions.

Data Analysis

The research process followed the steps shown in Figure 5. The set of 63 reports from Fall 2022 were read repeatedly by the first author to understand how students were responding to the prompt to compare spectrophotometry and gravimetric analysis as methods for determining the formula of hydrated copper compounds. This lets the researcher build a sense of the data as a whole and to move purposefully away from a first-order perspective.[65] The first cycle of coding used Initial Coding[66] to begin breaking down the data to search for the similarities and differences in student responses as they compared the two methods. In the process, a series of concept maps were developed from these comparisons that described students' attitudes relating to either spectrophotometry or gravimetric analysis as the better (or worse) method (see Figure S1-S4 in Supporting Information).

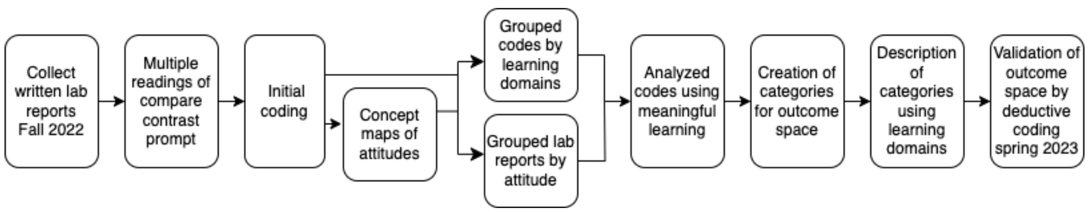


Figure 5. Methodological flowchart of the research process. 63 randomly collected lab reports provided the unit of analysis from which codes, categories and the outcome space were derived.

Out of the Initial Coding and concept maps, reports were grouped by the students' expressions of their preference for: spectrophotometry (n=25), gravimetric analysis (n=13), or neither (n=25). This provided a vehicle to observe patterns in student written attitudes towards the two analytical techniques. In this case, we use the definition of "attitude" as given by Eagly and Chaiken: "attitude is a psychological tendency that is expressed by evaluating a particular entity with some degree of favor or disfavor."[67] Their formulation has a three-part analysis of attitude that reveals that evaluative responses occur as cognitive, affective, and/or behavioral and are not easily separated from one another.[67,68] In our work, we align Eagly and Chaiken's categories with the cognitive, affective, and psychomotor domains developed and used by Bretz and coworkers. This alignment is presented in detail in Table S1 of the Supporting Information.

At this point, the Initial Codes were assigned to the three domains of meaningful learning[61]—cognitive, psychomotor, and affective. This was accomplished by considering whether a segment that had an Initial Code expressed: their engaging with concepts, ideas, relationships, and mental processes of the labs which was coded within the *cognitive* domain; if the segment referred to the student expressing something that was done with material or equipment, then it was coded within the *psychomotor* domain; and if the segment referred to student attitudes, values, interests or achievement motivations,[69] then it was coded within the *affective* domain. Our affective coding is guided by the explicit vocabulary and concepts associated with affective research in chemistry,[68,70–72] so that we recognized affective segments by students' explicit statements (e.g., of struggling or having difficulty, or processes they described as easy or complicated). In this manner, we also assigned indications of perceived control over and responsibility for their own learning as reflective of affective learning.[7073,74]

Some segments of student writing were coded for multiple areas of learning. For example, when a student writes that they were successful or that a process was time-consuming, it was coded as cognitive and psychomotor respectively, but also coded as affective which is consistent with the literature on affective learning in the lab.

Initial coding analyzed only student responses to the compare and contrast prompt. As the coding progressed, the analysis was expanded to deductively code additional sections of students' lab reports (e.g., prompt to explain how they arrived at their formulas, sample calculations, reported ratios) to provide further data on students' understanding of and experiences with the lab. These codes were revisited and modified using the framework of phenomenography, ensuring that students' written perceptions were the focus of the analysis.

The coding scheme continued to be elaborated until saturation occurred (i.e., no new codes presented themselves). Codes were combined into intermediate groups based on similar perceptions as expressed in student reports. These groups were further organized into subcategories and organized within the learning domains into a coding scheme. This coding scheme was given to a second coder who used it on 10% of the documents. There was 85% code occurrence agreement between the two coders. Differences were discussed and resolved before the coding scheme was finalized (Table S2 in Supporting Information).

Using the final coding scheme and the original coding from the student data, a phenomenographic outcome space was created in which the categories of description—the distinct perceptions about the phenomenon—were described using the three learning domains as crosscutting themes (see Table 1 in Results).

To validate the outcome space, the first author returned to the entire data set of student reports (N=280) and randomly selected student reports that were coded until all categories of description from the initial set of 63 reports were found again in the data. This occurred after 17 student responses. During this validation process, no new insights about student perceptions were uncovered.

Similarly, as an additional test of the validity of the outcome space, consented student reports from the spring 2023 semester were randomized and deductively coded using the coding scheme derived from the fall 2022 data set. Coding continued until all categories of description and their crosscutting themes had been identified which occurred after the tenth lab report was analyzed. No new codes, themes, or perceptions presented themselves in the data set from the spring of 2023.

RESULTS

In our analysis of students' written lab reports, we uncovered four distinct categories of description for the perceptions students provided about using spectrophotometry for determining hydrate formulas. These students were typically able and confident using gravimetric analysis as noted by Braylen: "That method was significantly less intensive and much easier to set up." Table 1 contains the category of description, its short name, and a brief description. Table 2 contains the categories of description and describes how the categories aligned with the cross-cutting themes of cognitive, psychomotor, and affective learning. It is important to note that while these are distinct perceptions of students in the lab, individual students may hold more than one perception at any time.[52,56,75] It will be seen in Table 2 that the category "Spectrophotometry is a black box and calculations to find a formula" does not have information in the affective domain for the fall 2022 data set but there was a negative affective expression in the spring 2023 data set.

Table 1: Categories of description, their short name, and a brief description of each.

Category of Description	Short Name	Description
Spectrophotometry is the interaction of light with matter and the calculations to describe matter	Interaction of light and matter	Reflects a perception based on understanding that spectrophotometry is a theoretically grounded process using light-matter interactions.

Spectrophotometry is a specialized instrument and the calculations to describe matter	Instrument and property of matter	Covers the perception that absorbance is a property of solutions that can be used in calculations but is not as reliable as mass.
Spectrophotometry is a black box and calculations to find a formula	Black box and calculations	Encompasses a perception that sees absorbance as a number that comes out of the spectrophotometer and is used to calculate the formula.
Spectrophotometry is complicated to understand, use, and explain	Too complicated	Used for the perception that students did not express understanding absorbance as a property, the spectrophotometer as an instrument, or how to move from measurements to the formula.

Table 2: Student Perceptions of Spectrophotometry Based on Written Responses in their Lab Reports

<table>
<tr><td></td><td colspan="7">Categories of Description</td></tr>
<tr><td>Student Perception / Cross-Cutting Theme</td><td colspan="3">Spectrophotometry is:
Too complicated</td><td>Spectrophotometry is:
Black box and calculations</td><td colspan="2">Spectrophotometry is:
Instrument and a property of matter</td><td>Spectrophotometry is:
Interaction of light and matter</td></tr>
<tr><td>Cognitive—Understanding of Spectrophotometry</td><td colspan="3">• Expresses that spectrophotometry is a machine that may or may not work
• Expresses misunderstanding about using absorbance to determine concentration and how to use calculations to get the formula.</td><td>• Expresses that the computer gives absorbance which is used in calculations to determine the formula.
• May express misunderstanding of calculations to get the formula.</td><td colspan="2">Expresses an understanding that absorbance is a value of the solution which can be used to get concentration, and that concentration along with other measurements can get formula.</td><td>Expresses an understanding of relationship between matter, light, and numbers, and uses these to calculate formula.</td></tr>
<tr><td>Psychomotor—Interaction with matter and equipment</td><td colspan="3">• Expresses doing something with the material which is unrelated to spectrophotometry or with how they “used” the computer.
• Expresses doing something with the hydrate, but the description is incomplete or incorrect.</td><td>Expresses spectrophotometry as exclusively the calculations from measurements without reference to interacting with the matter or using the spectrophotometer.</td><td colspan="2">Expresses their interactions with matter at the intersection of matter and measurements</td><td>Expresses their interaction with matter at the intersection of matter and measurements</td></tr>
<tr><td>Affective—Attitude toward spectrophotometry</td><td>Expresses a negative attitude which is linked to the difficulty with the technology/ computer and the complexity of the steps</td><td>Expresses an uncertain attitude between the time-consuming nature of gravimetric analysis and many calculations in spectrophotometry</td><td>Expresses a positive attitude because the results seem more accurate.</td><td>N/A</td><td>Expresses negative attitude because absorbance not directly related to matter.</td><td>Expresses positive attitude because there is less handling of matter to cause errors.</td><td>Expresses a positive attitude toward spectrophotometry as accurate, comprehensive, and helpful, so student is “able to understand.”</td></tr>
</table>

In presenting our results we trace the categories of descriptions from where meaningful learning is limited to where it is more sophisticated. This is an example of a hierarchical outcome space, which is used when the experience of students ranges from less to more complex. This occurs in the context of the three learning domains to show that the progression of more sophisticated learning is occurring across all three domains.

"Too complicated" category

This student perspective about spectrophotometry expressed misunderstanding of what absorbance was, what the spectrophotometer was doing, and what the students were doing in the lab.

Cognitive domain. Writing that expressed this perspective often contained an attempt to describe what the spectrophotometer measured, but it included significant confusion. The confusion was evident in Maria's explanation of using the spectrophotometer:

> "The spectrophotometer is a device that measures the depth of mild relative to shade. This is used to decide how a great deal of light is absorbed by a colored chemical dissolved inside the solution."

Additionally, these reports contained incorrect explanations of both procedures and calculations as typified in Hanna's explanation:

> "You use the wavelength with the highest absorbance allowing you to get all the accurate data and receive the proper measurements of amount of compound and water."

In this perspective, the concepts seemed to get confused in the complexity of the process.

Psychomotor domain. As with conceptual gaps, the references to the psychomotor domain in this category were also misaligned. Typically, this perspective referred to doing something students were familiar with, such as reading the meniscus or drying glassware, but which was unrelated to spectrophotometry. As stated by Beryl:

> "I believe that recording through this current lab was something I struggled with since my measurements of the meniscus was probably off, and how the spectrophotometer didn't really show the data at the exact wavelength, so I just approximated the location on the program."

Affective domain. In the "too complicated" perspective, there were several different expressions of feelings about spectrophotometry which appeared in the data. Some writings pointed to a distrust of the technology as seen in Nana's rejection of spectrophotometry and favoring gravimetric analysis:

"I believe that the previous week's lab used a more accurate method in determining the final formula. I found that the computer system was proving to cause issues for our procedure as well as for others."

On the other hand, some embraced spectrophotometry with an apparent confidence in the technology as seen in this response by Viviana:

"The machine measuring the absorbance might not be 100% accurate...but it does seem more reliable.... If I had to choose between these two methods ... I would choose to use the spectrophotometric [*sic*]...."

Other responses showed positive affect toward spectrophotometry because it was quicker as seen in this section from Patty's report:

"However, it [gravimetric analysis] ... was very time consuming. We had to wait 40 minutes for the dehydration to happen.... This experiment [spectrophotometry] on the other hand was able to give us extremely specific results... being quite quick...."

"Black box and calculations" category

This next perspective expressed that the spectrophotometer produced a value known as absorbance, but did not relate absorbance to light or matter, to the light-matter interaction, or to anything they did in the lab.

Cognitive domain. Students with this perspective expressed that the computer gives absorbance which is used in calculations to determine the formula. Without any description or explanation of spectrophotometry, Danielle wrote:

"...we did spectrophotometric analysis to get absorbance and the concentration of the salts leading towards the moles of the salt and then grams. After which ... with mass of salt to get mass of water, moreover, getting moles of water. Hence also performing mole ratio to get number of water molecules."

For these students, spectrophotometry was a series of numbers and calculations through which they arrived at the final answer: the number of moles of copper, of water molecules, and of the mole ratio.

Psychomotor domain. In their writings, there was a noticeable lack of description of their physical interaction with the materials and the equipment of spectrophotometry. This is even as they were highly descriptive of the psychomotor in gravimetric analysis. This can be seen in Nicole's comparison of the two processes:

> "In Experiment 3, we conducted an experiment by *directly extracting* water from copper(II) chloride hydrate… In Experiment 4, we *calculated* the number of moles of copper(II) sulfate and water molecules in copper(II) sulfate hydrate using molar concentration and Cu^{2+} absorbance, then we calculate …." (Emphasis added)

Students with this perspective describe doing something psychomotor in gravimetric analysis (e.g., heating, dehydrating, weighing, spilling, waiting). Yet when those same students described spectrophotometry, the "doing something" was cognitive (e.g., calculating, reading, determining, using spectrophotometry. These descriptions of spectrophotometry are as a set of readings and a series of calculations from data provided by the computer.

Affective domain. In the data we collected from students in the fall of 2022 there were no affective references from students expressing the black box and calculations perspective. There was one student in the data set from spring 2023, Alex, who expressed a negative attitude toward spectrophotometry as seen in the statement concerning accuracy in spectrophotometry. They wrote:

> "This week's lab was not as accurate because none of the water molecules were liberated in the procedure. We did not have data of the salts after they were dehydrated so it was not as accurate of a calculation because it was also based off the absorbance values…."

In this report, misunderstandings in the cognitive domain are associated with a negative attitude toward spectrophotometry.

"Instrument and property of matter" category

These students' writings suggested an understanding that the spectrophotometer gave them an absorbance value that related to concentration, and that they were cognizant of their physical involvement in the lab.

Cognitive domain. These students expressed that absorbance is a value of the solution that is related to the concentration of the solution and useful for determining concentration in the unknowns. As written by Bertha:

> "Using the different levels of absorbance and the molarity it was related to, I created a graph and formed a calibration curve … which could then be used to determine the molarity of the different salts given."

They also expressed that the absorbance of the unknowns can give them the concentration. Helene wrote: "By creating a calibration curve (by creating dilutions) and getting the measured absorbance of each solution, we calculated the concentrations of Cu^{2+} in each solution."

Students with this perspective emphasized the functional use of spectrophotometry to give them a measurement of the substance.

They described in their lab report all the steps needed to arrive at the formula of the hydrate. They saw the calculations as complex and multi-pathed and were able to introduce measurements at the appropriate time in their explanations. This was consistent in the more sophisticated perceptions and lacking in the lower perceptions. Here Braylen described the complexity of the process:

> "Then using the moles calculated I multiply it by the molar mass of $CuSO_4$ to discover the mass of the $CuSO_4$ which was .207 g. Going back into the moles of the $CuSO_4$… an unknown amount of water molecules attached to said salts."

Braylen's explanation expressed the understanding of moving from measurements to the molecule ratio but still does not describe absorbance as light's interaction with the molecules.

Psychomotor domain. These students wrote in terms of their physical involvement with the material, equipment, and technology of the lab, not just calculations. Here, Ian described the difficulty of clicking on the uppermost point of the spectrum:

> "In Lab 4 [spectrophotometry], we used cuvettes filled with the salt solutions and a spectrophotometer to solve for the absorbance of the substance. This is way more susceptible to human error because it is difficult to accurately define the highest absorbance value based off the constant changing curve."

Additionally, these students integrated cognitive and psychomotor references in their explanations as seen in Ian's comparison above and in Helene's explanation:

> "After adding 20-30 mL of DI water, we found the mass of the solution, by again subtracting the mass of the flask with the solution by the empty flask."

Affective domain. When these students expressed feelings about the process of spectrophotometry, in some instances a tension existed. Some students saw it negatively as complicated and expensive but also as more accurate:

> "In comparison, spectrophotometric analysis is a much more complicated process overall and requires more expensive measuring devices and software, however it seems to give a more accurate result." (Braylen)

Conversely, there are some students in this perspective who expressed that spectrophotometry is not as accurate a method because absorbance is not directly related to matter. For these students who saw absorbance as a property of the solution, it was not as useful as mass. This perception was exemplified by Ian:

> "Compared to Lab 4 [spectrophotometry], the data from the Lab 3 [gravimetric analysis] was much more accurate as it directly reflected upon the mass amount of the salt rather than using absorbance data and a calibration curve equation to solve."

"Interaction of light and matter" category

This perspective was that the processes in the lab are theoretically grounded in light-matter interactions. These students related the theory to the measurements and calculations involved in finding the formula of the hydrate.

Cognitive domain. These students perceived spectrophotometry as a process with an understandable theory, going all the way from the data to the final analysis of the mole ratio. Cindy made this clear in describing the purpose of the experiment as "to understand how to use the absorption of light (color) to measure the concentration of a solution and to measure the moles." This was elaborated in Gert's writing:

> "Spectrophotometry is a method used to calculate how much light is absorbed by any given chemical substance. We measure the intensity of light as it passes through a sample solution, but the main principle of this method is that the compound absorbs or transmits light over a certain wavelength."

The common thread for this perspective is that spectrophotometry is described as the practical use of the interaction of light and matter as a tool rather than simply as a property or number generator.

Additionally, these students described the observations and data as a property of the substance. Gert's report notes, "we used the absorption of light to measure the concentration of a solution." These writings suggest that learning is occurring in the cognitive domain.

Psychomotor domain. These students' writing reflected their physical involvement with the material and equipment of spectrophotometry. In writing their explanations of getting the mole ratio, they described making the solutions, weighing the solid, and using cuvettes. In explaining some of the steps to use spectrophotometry to find the formula, Ernesto writes: "I need to measure the mass of solid and mass of Solution.... To calculate the mole of water, I used the mass of solid to subtract the mass of anhydrous compound." Likewise, Julia's summary description of the process to find the mole ratio involves a psychomotor component: "In this lab, we added water to the salts and used their absorbance rates [sic] to determine the concentration and the mole ratios of four different salts."

Affective domain. These students were likely to express positive attitudes toward spectrophotometry. While students were not asked to give feelings and attitudes in the prompt (i.e., compare and contrast), their expressions contained attitudinal responses. As Julia noted: “The spectrophotometric analysis method was preferred as it is more accurate and comprehensive.” Isla wrote, “As a comparison to these two experiments, the first one [gravimetric analysis] is more prone to error…. alongside being able to have a lot of errors, was very time consuming….” and Helene wrote: “In lab four, we also determined that the hydrate was $CuCl_2$ x $2H_2O$!” ending the statement with an exclamation point. In this category where students expressed an understanding of the absorbance of light, they were prone to evaluate spectrophotometry favorably.

In addition, none of the responses that fall in this category expressed negative feelings about spectrophotometry.

DISCUSSION

The four perspectives, or categories of description, in Table 2 fit into a hierarchically inclusive outcome space (Figure 6) in which they are arranged from the lowest order category (left) to the highest order categories (right).[49] In a hierarchical outcome space the higher order, more sophisticated perspectives include the lower order perspectives.[56,76] In this study, the categories of description are logically organized such that each successive perspective becomes more comprehensive in the perception of spectrophotometry. This is exemplified in how each category perceives the concept of absorbance: The “too complicated” category does not understand absorbance; the “black box and calculations” category perceives absorbance as a number from the spectrophotometer used in calculations; the “instrument and property of matter” category perceives absorbance as a property and used for calculations; and the “interaction of light and matter” category perceives absorbance as a measurement of the interaction of light and matter, a property of matter, and used for calculations. This hierarchical structure occurs across all three learning domains. By examining the relationship of the three learning domains within each of the categories, we are also able to discuss how meaningful learning does (or does not) reflect the relationship of those domains.

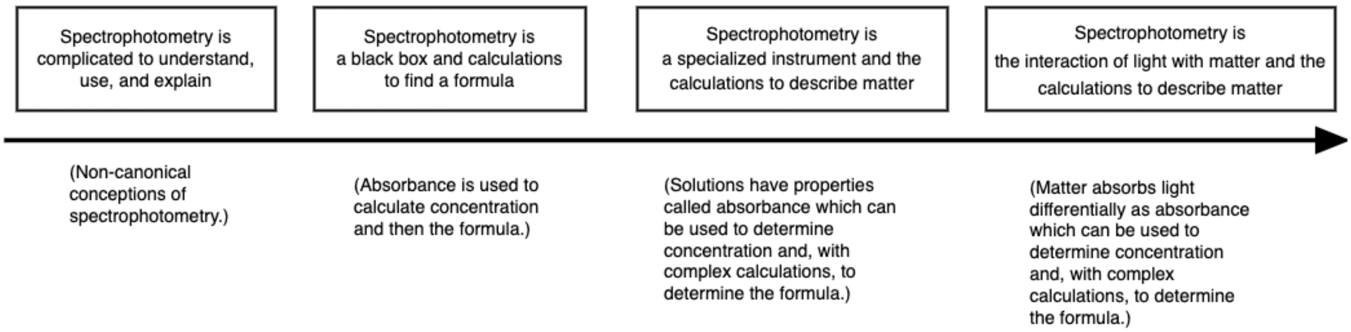


Figure 6. Graphical Representation of the Hierarchical Outcome Space. The categories of description are given in the boxes and as an example, the summary of the conceptual understandings is listed below showing the increased complexity of the students' perceptions from left to right.

Meaningful Learning

The phenomenographic outcome space shown in Table 2 and Figure 6 suggests that when students have a higher order understanding (i.e., "interaction of light and matter") perspective, they experience learning in all three domains and therefore meaningful learning in totality. Cognitively, the most sophisticated level sees students explaining that light and matter interact in spectrophotometry and that this interaction is differential both for light (wavelength max) and matter (shape of the absorbance spectrum). Their writings tie the theoretical underpinnings of spectrophotometry to its application in the lab. This perspective describes this interaction of light and matter—absorbance—as a property of matter with a direct relationship to concentration. Along with other properties—mass and volume—this perspective describes the complex process of moving from property measurements to formula as a multi-pathed set of calculations (Figure 4). Students in this "interaction of light and matter" perspective express feelings of satisfaction with spectrophotometry. In comparing it to gravimetric analysis, they evaluate it more positively in areas of accuracy, speed, and comprehension suggesting positive affect. They also describe their psychomotor involvement in the lab with references to being physically engaged with the material and equipment of the lab.

This perspective also documents a relationship or integration of the three learning domains. Where writings express positive affect, it relates to processes they are doing physically (e.g., not spilling) or conceptually (e.g., more data points are available). Additionally, this perspective describes spectrophotometry as both hands-on and calculations. Students who reported experiences in all three of these domains—those who can understand and work with the interaction of light and matter," also experience positive affect. This documents what full meaningful learning looks like in this laboratory setting.

Figure 6 and Table 2 document how the different learning domains shift as we move away from the most sophisticated perspective and how when learning goes wrong in one domain, it goes wrong in another. In the cognitive domain, as one moves down the hierarchy of perceptions, aspects of the sophisticated conception of spectrophotometry are lost, beginning with theoretical underpinnings, which are absent in the other categories. Cognitive understanding of absorbance is then lost in the category where absorbance is only a numerical value from the spectrophotometer that is useful to determine concentration. Finally, in the simplest perspective that we documented, cognitive understandings of the relationship of absorbance and the calculations are absent or incorrect.

Concurrent with this change in the cognitive characterization of absorbance and spectrophotometry is the change in psychomotor perception from a series of hands-on procedures with calculation in the two most sophisticated perspectives to a wholly calculations-based process in the two lowest order perspectives. Interestingly, the loss of psychomotor learning between the steps of the measurement and those of the calculations is more common in spectrophotometry than in gravimetric analysis. It appears that where mass is concerned, learning occurs more readily in the psychomotor domain. This suggests that even in the laboratory, when values lose their relationship to matter, the process to produce those values loses its importance.

Finally, as the perspective moves away from the higher level, the confidence and value students place on spectrophotometry decreases. As noted earlier, students did not hold absorbance in as high a regard as mass because it is not viewed as a real value. An exception to this trend is that in the lowest category, spectrophotometry was considered by some as more accurate because it uses technology (i.e., a computer and an electronic instrument) perhaps as Miller et al. suggest because they felt they were using “real-world” tools.[77]

We see in this study that when a property is relatable to the matter for which it is measured, like mass in the gravimetric analysis lab, then many students experience positive learning in the three domains and therefore meaningful learning is occurring. On the other hand, with a property like absorbance which, for many students, is not easily tied to the matter, there is the unlikelihood of meaningful learning. The implications of this will be discussed in a later section.

This discussion of the hierarchical nature of the outcome space for Table 2 and Figure 6 points to how the complexity of the measurement process and calculations contribute to an interruption student meaningful learning student learning. Both processes, gravimetric analysis and spectrophotometry are used as analytical tools to determine the hydrate formula, but the multi-path nature of spectrophotometry (see Figure 4) adds complexity appears to disrupt student learning. Students with the less sophisticated perceptions of spectrophotometry make mistakes in their explanations of the process or spectrophotometry or fail to describe it at all, choosing to focus on the calculations only. This is consistent with cognitive load theory, something we will explore in later studies.[78]

Implications

The results of this study have implications for both research and teaching. The relationship of students' perceptions across all three learning domains and the challenge of the complexity of spectrophotometric analysis points to the need to understand how students handle complexity as part of a learning environment and how to support them. While it has been assumed that the laboratory experience is inherently psychomotor, some students are not perceiving all lab work as psychomotor. Complex processes and properties may be leading these students to view lab work as merely a cognitive process and the physical presence of students may not be enough to elicit learning in this domain. Both researchers and educators may need to reengage the psychomotor domain when studying meaningful learning in the laboratory, especially when the relationship of measurements to chemical concepts are complex or branched (Figure 4).

Understanding the relationship or integration between the different learning domains, as is done here, is also an area where additional research is needed. Where students understand the theoretical underpinnings of a process, like spectrophotometry, this impacts their psychomotor and affective learning. This adds to the findings of An and Holme that providing information about instrumentation can improve students use of instruments,[26] and Miller et al., that students using instrumentation in the lab preferred to understand it conceptually before learning to use an instrument.[77] Unfortunately, many students do not understanding the theory behind spectrophotometry suggesting the need for more research into why students are not learning the theory even as they express their preference to understand it first.

There is also recent research into student perceptions of light matter interactions.[9,14,24] This study adds to that research and provides a framework for asking why students are neither perceiving absorbance as the interaction of light and matter nor as a property of matter in the lab.

There are also methodological implications for researchers from this work. Our results show how written reports can be used as a data set for phenomenography and can be used to elucidate the various ways a group experiences a lab activity. In asking students to compare analytical techniques and analyzing their responses, insight into student perceptions can be documented. Additionally, by grounding the study in meaningful learning with learning domains acting as crosscutting themes, patterns emerge giving evidence of student learning (or not learning).

For educators, this study can inform the development of lab curriculum and guide the focus of instruction for more meaningful learning. This study suggests that one can look at the more sophisticated categories of a phenomenographic study for guidance in developing learning outcomes and grading rubrics. It also provides clues into where learning is not occurring and misconceptions of students which need to be addressed. While the light-matter interaction is foundational to many analytical tools in chemistry, our study points to the need to better scaffold this concept in the context of the undergraduate laboratory. The use of a spectrophotometer does not guarantee that students understand light-matter interactions or absorbance as concepts. As students are prone to use and trust analytical tools they understand conceptually,[77] the teaching lab needs to include explicit instruction in the theoretical basis of the instruments, in this case, spectrophotometry.

We have also seen that when the process is mathematically complex, some students lose the sense of doing lab and instead collect numbers and calculate answers. Educators need to think about what the laboratory process looks like to students and consider ways to help students manage the procedural and mathematical complexity of multi-step analyses. This may be an example of an element of the science and engineering practices that goes beyond those documented in the NRC *Framework* or the NGSS, which, after all, were written for K-12 settings.

LIMITATIONS

This study occurred in a single midwestern, urban university and may not reflect what students are perceiving in other institutions. It was stated as part of the consent process that participation in the study would not affect a student's standing in the course and that the second author, who had responsibility for assigning grades, would never know who had participated in the study. Even so, it is still possible that self-selection bias of participants could have occurred, and the reports obtained may not represent student perceptions. Additionally, the heavy involvement in the curriculum by the authors could lead to bias in our analysis. To counter this possibility, discussions occurred throughout the entire process with other faculty and researchers who were familiar with the course and with the theoretical and methodological frameworks of the study.

Phenomenographic studies are intended to reflect participant's authentic experiences. In this case, our primary data source was from a prompt students answered in an assessment setting. As a result, it is possible that students answered in a manner that reflected their interest in providing the "correct" answer, not their own experience. Also, since students were not probed concerning their responses student lab reports might not reflect the full extent of their perceptions. While these could be true, the focus of a phenomenographic study is not the perception of a single individual but the distinct perceptions of a group of people. We feel that in using a large sampling (n=63) we have uncovered the perceptions of this group of students.

CONCLUSION

The spectrophotometer is ubiquitous to the undergraduate chemistry lab and yet students' perceptions of spectrophotometry have been little studied in CER. In looking at student perceptions, this study uncovered several significant findings about student learning in the undergraduate chemistry laboratory. Where students have a robust understanding of light-matter interactions (cognitive), meaningful learning occurred in the spectrophotometry lab as this understanding was related to understanding complex multi-step procedures (psychomotor) and contributes to confidence in the results (affective). Unfortunately, many students do not have a clear understanding of this concept and they struggle to appreciate and effectively use this analytical tool. For many students, absorbance is only a computer-generated number with little relationship to the matter it measures. While students see mass as a real property of matter and can use it to move through a series of stoichiometric calculations, students do not perceive light's interaction with matter in the same way. Coupling this disconnect of light to matter with the complexity students perceive in using absorbance in stoichiometric calculations, it is clear why gravimetric analysis is preferred to spectrophotometry by many first-year undergraduates in the introductory lab. If students are to experience full meaningful learning and embrace spectrophotometry as the useful tool it is, we will need to scaffold student learning from the very core of the concept.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.] Example brief descriptions with file formats indicated are shown below; customize for your material.

Detailed description of the procedure; Attitude concept maps; Attitude alignment table; Coding scheme. (DOCX)

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