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How Students Use Scientific Instruments To Create Understanding: CCD Spectrophotometers

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In this study, we investigated how upper-division college students interacted with laboratory instruments to identify the characteristics of instruments that influenced students' construction of scientific understanding. Both professional chemists and chemistry students use scientific instruments to collect and analyze data, and the process of interpreting data should lead to a better understanding of chemical phenomena. Although scientific instruments can be used as tools to aid students' construction of understanding, little research has been done on the impact of these instruments on the construct of understanding. Because instruments are increasingly used in secondary and tertiary education, investigating the impact of instruments on students' understanding is important.

Prior research is limited but indicates that the use of instruments influences both students' understanding of chemical concepts and their attitudes toward learning. Nakhleh and Krajcik *(1, 2)* found that the type of instrumentation secondary students used to study acid–base phenomena influenced their understanding of those phenomena. Malina *(3)* reported that secondary students had a high interest in using laboratory instruments to study chemistry. Eichinger, Nakhleh, and Auberry *(4)* found that college biology students valued the visual display capability and the flexibility of computer-interfaced laboratory instruments. Instruments do seem to influence student understanding and attitudes, but we specifically wanted to understand the mechanisms by which this occurs. Therefore, we investigated how college students in an upper-division, introductory analytical chemistry course interacted with a CCD spectrophotometer to determine the affordances of the spectrophotometer that contributed to student understanding of aqueous solution chemistry.

Theoretical Framework

The ideas of distributed cognition *(5)* and Gibson's theory of affordances *(6, 7)* were used as a framework to help identify the characteristics of scientific instruments that affect learning. This framework provided useful insights into the role of laboratory instruments in shaping learning, allowing us to analyze how students used the tools and artifacts in their environment to support thinking and learning.

Distributed Cognition

Traditionally, constructivism has focused on the cognition and learning attributed to individuals. Distributed cognition has broadened the basic definition of constructivism to focus on how the individual and his or her environment synergistically create cognition and learning. In terms of a chemical metaphor, distributed cognition is to individual constructivism as Lewis acids are to Brønsted–Lowry acids. Distributed cognition does not frame knowledge as mental representations within individual minds; rather, distributed cognition frames knowledge as being manifested in activity. Therefore, knowledge is created in any interactive system. In the distributed cognition perspective, the term 'knowing', rather than 'knowledge', is a more appropriate description of what is known, and 'knowing' can be applied to any combination of individuals, groups, organizations, or artifacts in the environment. Knowing refers to the regular pattern of activity and interactions displayed in a given situation. Because those patterns of activity will vary depending on the context, the setting in which the activity and interactions take place is an integral component of what the actions mean. The analysis of what an individual or group knows would be determined by their participation in the setting being investigated.

The setting is an important part of the analysis of context in the distributed cognition perspective. The setting may 'know' some of the information necessary for an individual or group to accomplish a task because the setting may contain the structured information necessary for that task. Artifacts are seen as "the cognitive residue of prior actions crystallized in the object" *(8)*. The designer of the artifact incorporates knowledge into an artifact to aid in the accomplishment of a goal or task. This view of artifacts can place knowledge in objects as diverse as physical tools, notational systems (like algebraic equations), or algorithmic processes (like calculators and computers). Artifacts may be an essential part of an overall cognitive process. For example, objects as simple as paper and pencil can become storage devices for information that is too elaborate or error-prone to store in an individual's memory. Calculators or computers can carry out complex calculations that an individual may not be able to carry out alone. In each case, the overall cognitive process is distributed between the individual or group and the artifacts. Both the individual and the artifact are necessary components of cognition.

In short, distributed cognition does not frame knowledge solely as mental representations or even group activity; rather, knowledge is manifested in activity and interaction within a particular setting. From this perspective, knowledge is an emergent property of an interacting system and is distributed across or embedded in the interactive patterns of system elements. Distributed cognition has been used in many areas of research and development, including designing inquiry-based peer tutoring models *(9),* analyzing multimedia learning environments *(10),* school leadership practices *(11),* procedures in medical diagnostics *(12),* interdisciplinary collaborations *(13),* and collaborative environments in the workplace *(14–16).*

Theory of Affordances

"The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill" *(6).* An affordance is a perceived functionality and is dependent upon both the perceiver and the situation. For example, a typical laboratory thermometer is a sealed glass cylinder containing mercury and etched with evenly spaced lines and numbers. To a chemist, these physical properties are not what it affords; what it affords is the measurement of temperature. To a young child, the thermometer may afford nothing more than a plaything. And to an introductory chemistry student, the thermometer affords not only the measurement of temperature, but also affords the stirring of solutions. Although each person observes the same object, the affordances of the object will vary depending upon the person's perception of the object in his or her present situation. The affordance and the perceiver of the affordance exist reciprocally to each other. The concept of affordance has been used to analyze new communication technologies in the workplace *(17).* This concept has also been incorporated into theories describing a person's ability to use tools *(18, 19),* the developmental psychology of art *(20),* geographic information systems *(21, 22),* and the characteristics of unique identifiers such as universal price codes *(23).*

Affordances and Distributed Cognition

The main concept shared by the distributed cognition perspective and the theory of affordances is that people and their surroundings are interrelated; the affordance of an object depends on the perceiver's needs and situation. For example, the typical laboratory thermometer affords the measurement of temperature as well as the stirring of solutions. Similarly, a person can solve a mathematics problem with or without a calculator, but the cognitive processes involved in the two situations are different. Cognition will vary with context. Affordances make cognition more efficient because affordances organize and summarize detailed information into more manageable frameworks. Detailed characteristics may be recalled if necessary but ignored if not needed. We believe that the more cognition that is accomplished through affordances (as opposed to characteristics), the greater the level of information that can be cognitively processed and, in turn, the greater the possibility for deeper understanding (and learning). Distributed cognition has been used with the concept of affordance in the development and study of computer-based learning environments *(24, 25).*

Research Questions

Using the theoretical framework of affordances and distributed cognition, we investigated two questions:

1. What are the affordances (perceived functionalities) of CCD spectrophotometers that influence students' understanding of the chemistry of aqueous solutions?
2. What are the affordances of CCD spectrophotometers that influence students' interpretation of data pertaining to the chemistry of aqueous solutions?

Methodology

Participants and Setting

We observed an upper-division, introductory analytical chemistry course (CHM 321) that consisted of seventy college juniors and seniors who were primarily chemical engineering majors and chemistry majors. The course included a weekly laboratory session involving a variety of instruments. This course was chosen for three reasons. First, the students had a substantial amount of background knowledge about chemistry concepts and basic techniques before entering the course, yet many of the students were unfamiliar with the techniques used in this course. Students typically had experience using the Spectronic 20 in high school general chemistry and biology courses, as well as experience with infrared spectroscopy and chromatography in their organic course. No student had previous experience with the CCD spectrophotometer. Second, the course was designed to teach students about the instruments and the chemical concepts associated with the purposes and functions of the instruments. This educational focus on the connection between the purposes of an instrument and the chemical concepts associated with the instrument was a focus that is not typically seen in lower-level chemistry courses. Third, the course provided ample opportunity to observe students' interactions with instruments and a sizable sample of students to draw interview participants.

The students were observed using spectrophotometers for two reasons. First, in analytical chemistry courses throughout the United States, spectroscopy is the most frequently covered topic in both lecture and laboratory *(26).* Second, this course had three different experiments using spectrophotometers (a Spectronic 20, a computer-interfaced Spectronic 20, and a CCD spectrophotometer). While the CCD spectrophotometer was the focus of this study, the diversity of instruments and their applications provided opportunities for future research to broaden our understanding of the impact of instruments on student learning.

The CCD Spectrophotometer

The CCD spectrophotometer consisted of two major components: the spectrophotometer and the microcomputer (Figure 1). The spectrophotometer (next to computer) was manufactured by Spectral Instruments (Tucson, AZ). This 430 model CCD spectrophotometer consisted of a tungsten light source, spectrograph, and fiber optic solution probe. The light passed through fiber optic cable to the probe tip (Figure 2), exited the fiber optic cable, passed through the sample solution, reflected off the concave mirror, passed back through the sample solution, and was carried back though fiber optic cable to the CCD detector. The signal was transmitted to the computer via an RS-232 serial link. The computer (133 MHz Pentium-1, 16 MB RAM, 1.3 GB hard drive, 8X CD-ROM) was used to manage all functions, including initialization, calibration, and data gathering (via the Spectral Instruments designed, LabView executable software). Data were displayed in graphical format (absorbance verses wavelength, 350–950 nm with a bandwidth of 1.1 nm) and were exported to floppy disc in spreadsheet format (Excel) for data analysis.

The CCD Spectrophotometer Experiment

Students used the CCD spectrophotometer to measure the absorption spectra of three metal ion solutions and several solutions with various mixtures of these three metal ions. The students were given spreadsheet templates for data processing (smoothing curve, deriving derivative curve, and solving for solution concentrations), as well as detailed instructions on how to use these templates. The written objectives in this lab were: (1) to develop colored metal ion complexes using chelating agents, (2) to perform quantitative spectroscopy using solid-state imaging detectors, (3) to compensate for instrumental drift using first-derivative spectroscopy, and (4) to resolve multicomponent samples without separation via matrix algebra and multiwavelength data. During lecture, the instructor gave an overview of how the instrument functions and also emphasized that this experiment was included to simply expose the students to this analytical technique; it would not be on an exam.

During this study, students used the CCD spectrophotometer to collect the absorbance spectrum between the wavelengths of 350 and 950 nm for multiple solutions containing known concentrations of three metal ions. Each spectrum required less than one second to obtain (not counting probe cleaning time) and was displayed immediately on the computer monitor. Following the laboratory period, students used matrix algebra (via a spreadsheet provided by the instructor), to determine the calculated concentrations of the three metal ions in their last mixture (a pseudo-unknown) to examine the accuracy of this laboratory technique.

Data Sources

Four different forms of data were collected: (1) videotapes of students using the instruments, (2) field notes from observations made during laboratory periods, (3) students' voice journals, and (4) interviews. Videotapes of students using the instruments were analyzed to detect possible patterns in interactions between the students and the instruments. Field notes *(27)* were used to document any observations that might be missed on videotape and to document any of the researcher's insights while in the laboratory. Voice journals were constructed by asking students to record their verbal reflections on a laboratory assignment and their responses to specific questions that focused on the learning that occurred during the laboratory period.

Interviews

Interviews were conducted with one group of three students and two individual students. The interview had four parts implemented in one session. First, students were asked about their general understanding of the concept of absorption and how it related to the experiment using the CCD spectrophotometer. Second, students observed a videotape of other students using an instrument at critical junctures of the laboratory experiment. Students were asked to describe their thoughts about what they were watching and tell what they might have been thinking about when they were performing the same part of the laboratory assignment during class. Third, the students were asked to use the CCD spectrophotometers to collect data in the same manner as in their laboratory experiment and to use the 'think-aloud' technique, or to vocalize their thoughts while using the spectrophotometer. Fourth, after the students finished watching the videotapes and working with the instrument, they were asked probing questions to further explore their understandings of both the instrument and the chemical concepts underlying the experiment. The students were also requested to describe the characteristics of the instrument that helped or hindered their learning.

Data Analysis

One author (EGM), in collaboration with two chemistry education graduate students, transcribed and analyzed the data by constant comparative analysis *(28).* Field notes, voice journals, and one interview were initially read for emergent themes, and an initial coding scheme was developed from these themes. All data were coded using the initial coding categories while revisions and reorganization of the coding scheme were considered. Through coding and recoding, the final coding scheme (see Table 1), including subcategories,

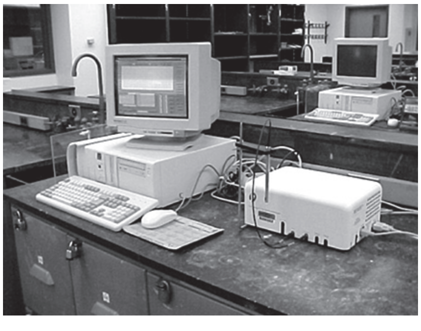

Figure 1. The CCD spectrophotometer in an actual laboratory setting.

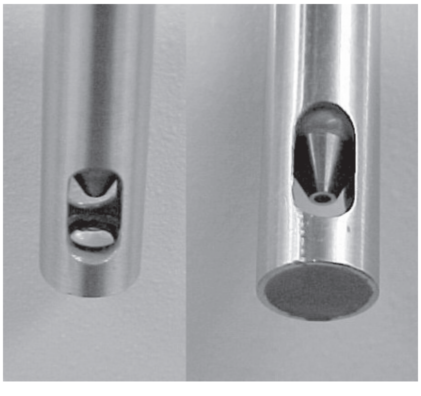

Figure 2. View of concave mirror (left) and fiber optic source in probe tip (right).

was developed and applied to all data sources. Categories 1–7 are all affordances of the CCD spectrophotometer, categories 8–10 capture students' background understanding, and category 11 captured students' specific recommendations. Our findings were developed from the trends seen in this final coding scheme.

Findings

Our findings fit into five general areas: (1) graphical display of data, (2) time, (3) error, (4) ease of use, and (5) other physical affordances. Each of these areas will be discussed individually.

Graphical Display of Data

For students, the primary affordances of the spectrophotometer were related to the graphical display of data. Students were able to use this feature of the CCD spectrophotometer to: (1) interpret their data, (2) discover unexpected results, (3) confirm the validity of their data, (4) make predictions about their solutions, and (5) check for error. A summary of supporting quotes for these five affordances of the graphical display is found in Table 2.

First, students used the graphical display of the spectrophotometer to interpret their data. The students understood absorption is additive when several colored compounds are in the same solution. They used this additive property, in conjunction with the absorption spectra of the individual compounds, to make predictions about the absorption spectra of their mixtures. Second, students showed immediate surprise when unexpected results were displayed. They compared the graphical display with their predicted images of what the spectra should look like. These unexpected results primarily occurred when students ran the nickel ion sample (the nickel

Table 1. The Final Coding Categories Applied to All Data Sources

Category	Subcategory	
1. Time	A. Quick or fast—general comments B. Out of lab ASAP	C. Faster than other labs D. Speed versus accuracy
2. Ease of use	A. General statements 1. Lab procedure 2. Instrument	B. Easier than other labs C. Easy procedure— no interpretation required
3. Error	A. Dilution or concentration error B. Contamination error C. Desire to limit or check for error	D. Procedural error E. Instrumental error F. Data-interpretation error
4. Learn by doing	A. Hands-on comments	
5. Data recording and gathering	A. General comments about procedure	
6. Other specific physical affordances	A. Procedural prompts B. Probe C. Probe holder D. Wavelength range	E. Data-processing ability F. CCD cover G. Computer H. Miscellaneous
7. Data interpretation: graphical	A. For error B. For validity C. For concentration	D. Expectations E. Meaning making F. General comments
8. Purpose	Comments on why we are doing this experiment	
9. Conceptual understandings	Comments showing conceptual understanding	
10. Instrumental understandings	A. Correct B. Incorrect	
11. Student recommendations	A. More instruments B. Ease of use C. Error	D. Learning by doing E. Specific physical affordance
12. Miscellaneous	A. “Not a hindrance” comments 1. To learning 2. Instrument	B. Other

ion had two peaks in the visible region and students only expected one peak) and the relatively flat spectrum produced by the solution containing all three ions (students typically expected the four peaks seen in the three spectra of the individual ions).

Third, students visually compared solution colors to absorption spectra to confirm the validity of the spectra, especially when the solutions contained the same proportions of each compound in solution but the overall concentration of the solution was increased. Fourth, students used the relative concentrations of the compounds in solution to make predictions of relative peak heights, shapes, and overall absorption intensities. Fifth, students used the speed of the data collection and processing to check for errors in their individual runs by performing "double runs" to make sure the spectra obtained were nearly identical.

In general, students understood the value of the computer-generated graphs. While this understanding was demonstrated in many of the students' statements and actions, these quotes from the group interview capture many of these themes:

> Interviewer: "What parts of the instrument helped you to interpret the data?"
>
> Roxanne: "Well, seeing the graph right away kind of helps."
>
> Sara: "That helps. That helps."
>
> Roxanne: "Sometimes you take just a number, then you have to go later and figure out the graph. It's too late to do anything about it. You can figure out if you're doing it correctly, or if you used the right solution."
>
> Sara: "Or if you had some error."
>
> Roxanne: "In preparing the solution" (Group Interview, Text units 175-180).
>
> Interviewer: "How did the CCD spectrophotometer aid in your learning during this course?"
>
> Roxanne: "I think the instrument helps, especially for this type of experiment when you're looking at the different peaks, where the peaks are at, and if they occur, so you can determine concentration. I think it was helpful" (Group Interview, Text units 191,194).

Time

Another affordance of spectrophotometers perceived in students' comments and actions was the affordance of time. Students perceived that the instrument was fast. They understood that the spectrophotometer was fast compared to other laboratory instruments and techniques, especially for the amount of data obtained. In every data source, students mentioned more than once that they used the speed of the spectrophotometer to help them leave the laboratory relatively early. Students reiterated that their primary motivation during class was to spend as little time in the lab as possible while still collecting enough good data to get a good grade. One student, Bob, expressed a few of these themes in his voice journal response to the question, "What parts of the CCD spectrophotometer were beneficial to you in conducting this experiment? How were these parts beneficial?"

> Its rapidity, number one. It did it, I think, in three-quarters of a second. It took longer to save than it did to do the actual experiment. Which is a big improvement over more traditional methods, which I could see as being cumbersome and boring and makes me never want to do chemistry ever again (Group Voice Journal, Text unit 26).

Table 2. Supporting Quotes for Affordances Relating to the Graphical Display of Data

Affordance	Supporting Quotes
Interpret their data	One of the things I look at is the fact that copper had a peak way farther along, so if any of the samples had copper, it would show up like around this one. This peak was closer to red... And this one had two small peaks, but if you superimposed them, like they were all in totally different regions so that you could actually…figure out what the composition is. (Erica Interview, Text unit 171)
Discover unexpected results	Betty just got done running sample A and directly went to run sample B. "Wow, that's different" was what she said when the sample B run came up on the screen. (10/12 Field notes, Text unit 8, also see quote below…Group Interview, Text units 100, 101)
Confirm the validity of their data	And you can see, it's higher up than the last one. [Looks at solution.] And it looks more concentrated than the last two. And I think we knew the concentrations, if we look in here [grabs lab manual and looks at chart showing the volumes used to make solutions], yeah, cause it was 5-5-5, 10-10-10, and 20-20-20. So it made sense that it was darker. (Erica Interview, Text unit 127)
Make predictions about their solutions	This is 5 of copper, 5 of cobalt, and 5 of nickel. [Runs spectrum] Huh! I didn't expect it to be like that, I expected there to be three peaks. I don't remember from what we had before. It's an equal mix, so maybe it's OK. (Group Interview, Text units 100, 101)
Check for error	I think it is valid, we can go on and see what the others look like. We can always rerun later. (Group Interview, Text unit 102)

While students were aware of the benefits that the speed of the instrument afforded them, they were also aware that the speed of the instrument came as a tradeoff to the potential accuracy of this technique. Erica expressed this idea after I asked her if there was any other information we could get from the graphs.

> Well, I guess one of the things I look at is the fact that they are really choppy, there is a lot of noise. … But then I would think, well, we did it really fast, so I would not expect it to be as accurate as anything else would. Because I used to work on a spectrophotometer that actually would take 20 minutes to run a sample. And that was accurate, there was very little noise on the sample.

Error

Students perceived error as one of the primary concerns of analytical chemistry, and the CCD spectrophotometer possesses some affordances impacting error. As mentioned previously, the speed of the instrument allowed students to do error checks quickly. Students recognized the probe as the primary error-causing part of the instrument, so they thoroughly cleaned and dried the probe to avoid contamination and dilutions of their solutions. Arthur expressed this negative affordance in his voice journal response:

> I was always concerned that I wasn't cleaning the probe good enough with the hole. It seems like water would get trapped in there, or your substance that you were sampling, so I don't know if it was always cleaned out good (Text unit 14).

The students even helped other students learn efficient methods for dislodging the water from the hole in the probe without having to insert a Chemwipe that could damage the optics. Because the CCD spectrophotometer was so simple to use, the students believed they were less likely to make procedural mistakes. Kathy expressed this idea after she was asked how the use of CCD spectrophotometer compared to the Spectronic 20.

> Well, the Spec 20 is…There you're a lot more hands-on, so you actually have to go a little deeper into what's going on to make sure you're doing the right thing. This [the CCD spectrophotometer] is much more user-friendly, but the fact that you have more work with the Spec 20 makes you understand the fact of what's going on. Because we used the Spec 20 before, I know we have a light source in there. You know, kinda the inner workings of the Spec 20, I guess, as a class. This is a lot better because you don't have the chance for error like with the Spec 20. If your cuvette is not clean you've got a problem. If the lid is not always closed you've got a problem. And then you're not as precise because you have to roll that little dial over there to get it exactly to zero. What if you're not exactly at zero? This is better because it's more user-friendly. You don't have as many sources for human error as you did with the Spec 20 (Kathy Interview, Text unit 471).

The computer software afforded the students protection from making certain procedural errors by keeping certain buttons inactive until it was appropriate to use them. For example, Erica had difficulty getting started with the spectrophotometer. The interviewer had initialized the instrument before the interview, but Erica was uncertain what to do before she started running samples. She quickly read through both the lab manual and the instructions for the spectrophotometer without discovering what she needed to do next. When she looked back at the computer screen and discovered that the 'Blank' button was active and the 'Sample' button was not, she assumed she had to run the blank first. After running the blank, the 'Sample' button became active, and Erica was confident that she was operating the instrument correctly.

Ease of Use

As previously mentioned, the students saw the instruments as easy to use. "It was fairly easy to use. I mean it is a pretty simple device. Well, it's complex, but it is simple to use" (Arthur Voice Journal, Text unit 13). As seen in Kathy's quote mentioned earlier, the fact that the instrument was easy to use reduced the amount of potential procedural error that the students could make. However, the fact that the instrument was so easy to use may have also potentially reduced the students' understanding of the chemical principles underlying the instrument's function.

The Spectronic 20 required students to perform many procedures by hand (calibration, wiping, inserting the cuvette, lining up the cuvette, etc.); therefore, the students felt a need to know about the internal function of the Spectronic 20. However, unlike the Spectronic 20, the CCD spectrophotometer only required rinsing and drying the probe, inserting the probe into the solution, and clicking the appropriate button on the computer screen to calibrate the instrument and collect the absorption spectrum. This ease of use of the CCD spectrophotometer, combined with the data processing capabilities of the computer, provided the students opportunities to spend more time thinking about the data on an interpretive level than thinking about the internal workings of the spectrophotometer. Depending upon the overall objective of the instructor—whether the students focus on interpreting data or understanding the internal workings of the spectrophotometer—the ease of use can be seen as a positive or negative affordance. In this particular experiment, the instructor wanted the students to focus on the analytical technique this instrument provided, thus the ease of use was a positive affordance.

Other Physical Affordances

Students also identified other affordances of the CCD spectrophotometer that were specifically related to the probe, such as the wavelength range of the instrument or the cover of the spectrophotometer.

The students saw the probe as having both positive and negative affordances. The positive affordance of the probe was ease of use, especially when compared to the cuvettes used with the Spectronic 20. However, the students perceived as a negative affordance of the probe that the possibility for error existed while using the probe. As previously mentioned, students had expressed their concerns about cleaning and drying the probe in order to avoid errors associated with contamination or dilution. Another negative affordance was the difficulty of operating the probe holder, even with multiple uses. The design of the probe holder allowed the holder to be moved up and down on a steel post mounted to the spectrophotometer so the probe could be placed in a solution at a specific height. Adjusting this mechanism was not easy, and students would typically remove the probe from the holder instead of using the holder to move the probe. Sara expressed her concerns about the probe holder during the group interview, “In lab, I remember fighting with this thing all the time. That’s what I was worried about, not breaking the stupid thing” (Text unit 110). This is a design problem that could easily be corrected by the manufacturer.

The wavelength range of the machine was seen as a positive affordance of the spectrophotometer. Instead of having to take individual points at each wavelength as with the Spectronic 20s, the students were able to take measurements at all wavelengths at once with the CCD spectrophotometer and then see the graph immediately. This reduced the amount of time the students spent taking data points, the amount of time they spent graphing data, and the amount of error students could make while running different samples. This affordance was not presented by the instructor but was described by students when asked how the CCD spectrophotometer compared to the Spectronic 20 or when asked what they saw as beneficial about the CCD spectrophotometer in conducting the experiment.

One student indicated she wanted to know what was going on inside the spectrophotometer. Erica expressed her dislike of the opaque cover for the CCD spectrophotometer by saying,

> What I think would be cool is, rather than of that plastic housing, if we could make it clear, so you could see what it looks like inside. It would probably, totally, disrupt the light, because you would get stray light in there, and you need darkness. But I think that would be cool, so you could see what going on inside there.

Additional Insights

Students expressed, both in the laboratory and in the interviews, that the person running the computer was viewed as running the ‘instrument.’ The person handling the probe was seen as just physically manipulating the solutions. For example, during the group interview the students were asked, “Did you actually operate the CCD spectrophotometer during lab?” Sara responded by shaking her head, “No.” Gary then stated that he had run the instrument during the laboratory period. When Sara was asked what she had done during the experiment, she indicated that she had rinsed the probe and placed the probe into the solutions. Although the probe was the device that enabled the students to measure the absorbance of the solution over a wide range of wavelengths, the computer was seen as the ‘instrument.’

We speculate that the students perceived more affordances in the computer portion of the CCD spectrophotometer. Thus, the students saw the overall value of the computer as being greater than the overall value of the spectrophotometer and considered the computer to be the ‘instrument’. This perception could possibly be overcome with more specific instruction. The students in this study did not receive any specific instruction pertaining to the function of the various parts of the instrument, only an overview of the instrument’s design in schematic form.

Conclusions: Preliminary Assertions and Implications

Students, in general, recognized the graphing capability, speed, ease of use, and ability to check and limit the amount of error as affordances of the CCD spectrophotometer. Yet, “…the student mentality [is] not always to learn the theory behind it, it’s to do the minimum you have to do get the grade, to get done, to get the A” (Roxanne, Group Interview).

According to the distributed cognition perspective, students perceive the affordances of instruments that help them accomplish their goals. For the students in this analytical chemistry laboratory, the overall goal was to get error-free data that could be used later to solve for the concentrations of their unknowns and to get that data as quickly as possible. Students used the graphing capability of the spectrophotometer to check to see whether their data were valid with minimal errors. The speed and ease of use of the instrument allowed the students to do this quickly with minimal chances for human error.

Experimental designs and objectives influence the affordances that students perceive in the instruments. Because the instructor-defined goal of this experiment was to solve for the concentrations of the unknowns, many students were able to learn how to use the instrument to meet that goal without having to understand the internal workings of the instrument. The students were able to focus on the features of the instrument that would help them accomplish that goal while ignoring the features of the instrument that were not useful to them. If the goals of the experiment were to have the students understand the internal workings of a spectrophotometer, the speed and ease of use of the CCD spectrophotometer would have been hindrances to the students’ accomplishing that goal. Therefore, it follows that instructors must be cognizant of their objectives for instrument use in a laboratory setting and choose instruments and procedures that are consistent with those objectives. Students recognize and use the affordances of the instrument that allow them to accomplish their goals in the laboratory—whether their goals are to finish the lab quickly and receive a good grade or to achieve the instructor-defined objectives of interpreting data or understanding the internal workings of the instrument. Instructors should therefore choose an instrument and procedures that emphasize the goals that they have for the students’ learning.

Affordances Affecting Learning

Students were observed, on occasion, talking about chemistry concepts during their use of the CCD spectrophotometer; however, the dialog observed indicates that these concepts were probably understood prior to performing the experiment. For example, students talking about absorbance would be discussing how one metal ion absorbed more at a particular wavelength than did another metal ion, or how the solution that was twice as concentrated had absorbance values that were twice as large. We speculated that much of conceptual laboratory learning would take place outside of the actual laboratory, primarily during the construction of the laboratory report. We had two indicators to support our speculation. First, Nakhleh and Krajcik *(1)* found that most of the high-school students’ statements when using scientific instruments were procedural, especially when students were first learning to use a particular instrument; thus, students were preoccupied with physically manipulating the instrument rather than with conceptual thinking. Second, "…the student mentality [is] not always to learn the theory behind it, it's to do the minimum you have to do get the grade, to get done, to get the A" (Roxanne, Group Interview). Students typically are not intrinsically motivated to think about conceptual ideas during the laboratory period. Students should be encouraged to think about the conceptual aspects of laboratory experiments by asking appropriate questions during the laboratory period. These questions are typically presented to students as questions to be answered in their discussion sections of the laboratory report. We speculate that conceptual learning in the laboratory could be enhanced if the laboratory instructors would ask their students to explain their conceptual understanding of the instruments and the experiment during the actual laboratory period.

Future Research

This research has focused on several students interacting with one instrument; thus our present findings may not apply to all laboratory instruments. However, we plan to observe students' interactions with several instruments during various experiments in order to determine the positive and negative affordances of these instruments. We hope this work will inform the way laboratory experiments are designed and implemented. Additionally, we hope to discover affordances that are common to all scientific instruments.

Another possible implication of this research is that students must physically interact with the instrument in order to take full advantage of all the affordances of the instrument that influence learning. One student, Kathy, remarked that she did not feel like she was learning unless she was directly interacting with the CCD spectrophotometer (Kathy Interview, Text unit 459). Even though only one student stated this idea, it is consistent with our theoretical framework. Future research is needed to explore this idea in depth.

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Literature Cited

1. Nakhleh, M. B.; Krajcik, J. S. *J. Res. Sci. Teach.* **1993,** *30,* 1149–1168.
2. Nakhleh, M. B.; Krajcik, J. S. *J. Res. Sci. Teach.* **1994,** *31,* 1077–1096.
3. Malina, E. G. The Impact of the Purdue Instrument Project on Secondary Chemistry Student Learning and Attitudes toward Science. M.S. Thesis, Purdue University, West Lafayette, IN, 1999.
4. Eichinger, D. C.; Nakhleh, M. B.; Auberry, D. L. *J. Comp. Math. Sci. Teach.* **2000,** *19,* 253–275.
5. *Distributed Cognitions: Psychological and Educational Considerations;* Salomon, G. Ed.; Cambridge University Press: New York, 1993.
6. Gibson, J. J. *The Ecological Approach to Visual Perception;* Houghton Mifflin: Boston, 1979.
7. Gibson, J. J. *Reasons for Realism: Selected Essays of James J. Gibson;* Erlbaum: Hillsdale, NJ, 1982.
8. Cole, M.; Engeström, Y. In *Distributed Cognitions: Psychological and Educational Considerations;* Salomon, G. Ed.; Cambridge University Press: New York, 1993; pp 1–46.
9. King, A. *Educ. Psych. Rev.* **1998,** *10,* 57–74.
10. Psotka, J.; Kerst, S.; Westerman, P.; Davison, S. A. *Computers Educ.* **1994,** *4,* 285–294.
11. Spillane, J. P.; Halverson, R.; Diamond, J. B. *Educational Researcher* **2001,** *30,* 23–28.
12. Lebeau, R. B. *Educ. Psych. Rev.* **1998,** *10,* 3–24.
13. Derry, S. J.; DuRussel, L. A.; O'Donnell, A. M. *Educ. Psych. Rev.* **1998,** *10,* 25–56.
14. Decortis, F. *Int. J. of Human-Computer Studies* **2000,** *53,* 5–33.
15. Madhavan, R.; Grover, R. *Journal of Marketing* **1998,** *62,* 1–12.
16. Clegg, C. *British J. Psych.* **1994,** *85,* 449–477.
17. Burgoon, J. K.; Bonito, J. A.; Bengtsson, B.; Ramirez, A., Jr.; Dunbar, N. E.; Miczo, N. *J. Management Information Systems* **1999–2000,** *16,* 33–56.
18. van Leeuwen, L.; Smitsman, S.; van Leeuwen, C. *J. Educ. Psych.* **1994,** *20,* 174–191.
19. Lockman, J. L. *Child Development* **2000,** *71,* 137–144.
20. Pufall, P. B. *Human Development* **1997,** *40,* 169–180.
21. Webster, D. S. *Antiquity* **1999,** *73,* 915–917.
22. Llobera, M. *Antiquity* **1996,** *70,* 612–622.
23. Paskin, N. *Proceedings of the IEEE* **1999,** *87,* 1208–1227.
24. Oshima, J. *J. Educ. Computing Res.* **1998,** *19,* 329–351.
25. Hewitt, J.; Scardamalia, M. *Educ. Psych. Rev.* **1998,** *10,* 75–96.
26. Girard, J. E.; Diamant, C. T. *J. Chem. Educ.* **2000,** *77,* 646–648.
27. Patton, M. Q. *Qualitative Evaluation and Research Methods*, 2nd ed.; Sage: Newbury Park, CA, 1990; pp 239–244.
28. Strauss, A.; Corbin, J. *Basics of Qualitative Research. Techniques and Procedures for Developing Grounded Theory,* 2nd ed.; Sage: Thousand Oaks, CA, 1998.