AC 2009-1286: COMPARISON OF STUDENT PERCEPTIONS OF VIRTUAL AND PHYSICAL LABORATORIES

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Comparison of Student Perceptions of Virtual and Physical Laboratories

Key words: metacognition, experimental design, virtual laboratory

Abstract

This paper presents an analysis of student survey responses after completion of three different laboratories, two physical laboratories and a virtual laboratory. Students' perceptions of the three different laboratory experiences are discussed from the focus of intended (metacognitive questions) and actual learning (cognitive questions). The student responses were coded by three researchers, the coding process was modified to increase the interrater reliability from around 0.7 to around 0.9 and was verified by two independent coders. Student perceptions about the laboratory experiences were also correlated to student performance in the class, as measured by the students' scores on all graded assessments for the course. Analysis of metacognitive statements of students show enhanced awareness of experimental design, and greater occurrences of critical thinking and higher order cognition in the virtual laboratories. These statements are consistent with the type of learning that has been previously measured for one of these virtual laboratories, particularly through a think aloud protocol that has been reported elsewhere.

Introduction

The undergraduate laboratory plays a pivotal role in science and engineering curriculum, especially in the context of developing students' abilities of scientific inquiry and engineering design. The pedagogical value of the hands-on experience that a laboratory provides is ubiquitously endorsed by educators;[1] however, in practice the engineering laboratory has limitations as well. Laboratories are resource intensive, both in terms of acquiring and maintaining the equipment and in terms of staffing requirements. A possible way to overcome these limitations of the traditional physical laboratory is to use alternative modes of delivery, such as virtual laboratories. In a virtual laboratory, students do not interact with real equipment to obtain data, but rather with computer simulations of laboratory or industrial process equipment, obscured by pre-programmed statistical variation. The virtual laboratory is intended to allow future engineers to practice the skills they will need in industry, in much the same way a flight simulator is used for training pilots. This learning environment is compelling not only because it can alleviate resource constraints, but also because it can address learning outcomes not possible with a physical laboratory. In contrast to a physical laboratory experience, data collection is performed virtually, and therefore, consumes a relatively small amount of the student's cognitive load.[2] Thus, student effort can be expended on problem scoping (including information gathering) and developing an experimental strategy to explore the design space and solve the problem. In other words, students can invest cognitive load on developing their schematic knowledge in the analysis and interpretation of the data, and also on developing strategic knowledge as they make decisions and iterate on the design solution.

With varying instructional purposes, virtual laboratories have been developed and integrated into engineering curricula in a wide variety of disciplines.[3-9] Virtual process laboratories based on traditional chemical engineering processes such as styrene-butadiene copolymerization[10] or hydrogen liquefaction[11] have been developed at Purdue and, more recently, a visually impressive set of virtual reality process examples have been implemented at three universities in Australia.[12]

However, relative to the work on instructional development, investigation of how virtual laboratories have impacted student learning has been sparse.[13-16] A greater understanding of the types of cognition a virtual laboratory promotes in students is needed. The study presented in this paper is based on the metacognitions of students as they engage in laboratory experiences. Its intent is to compare students' perceptions of key cognitive processes and specific content in the virtual laboratory to the physical laboratory.

Metacognition as a regulatory activity involves students thinking about their thinking in a way that externalizes their perceived knowledge gain and knowledge awareness.[17] Research in metacognition in engineering education has demonstrated the efficacy of providing students with learning environments that enhance students' regulation of their own learning.[18] The perspective of formative assessment processes[19] indicates that student self-assessment defines what students understand about the goals and objectives of their learning experiences. Student understanding of the goals of learning experiences is a critical element in student acquisition of the content understanding and deep cognitive and procedural skill development in higher education. Metacognition as the process of students monitoring their own learning is an important element of student learning in the engineering context.[20]

The study presented in this paper seeks to identify how students' perceptions of their knowledge and awareness of their own learning evolve as they move through three structured laboratory experiences. The first and third laboratories are physical laboratories, based on the unit processes of ion exchange and heat exchange. The second is a virtual laboratory. Students were allowed to choose between two virtual laboratories, the Virtual Chemical Vapor Deposition (CVD) Laboratory and the Virtual Bioreactor (BioR) Laboratory. The intent of the research is to investigate the hypothesis that the virtual laboratory provides a context in which the students' perception of the laboratory experience will move away from acquisition of technical skills and application of bounded knowledge to using conceptual systems to generalize problem solving beyond the immediate context of the laboratory problem.[21] This study is part of a larger project to compare and contrast the nature of learning elicited in the virtual laboratory experience with that of a hands-on laboratory experience. By determining how students develop key cognitive processes and specific domain content in a virtual environment, the role of the virtual laboratory as an effective curricular tool can be constructed.

Laboratory Description

This study analyzes students' perceptions of their own learning in three laboratories in the first quarter of the capstone laboratory sequence in the School of Chemical, Biological and Environmental Engineering at Oregon State University. Of the two physical laboratories, the specific content in the Ion Exchange laboratory is new to most students, although it draws upon concepts well grounded in the curriculum; on the other hand, the Heat Exchange laboratory draws from material in the core junior level heat and mass transfer sequence, *Transport Phenomena II and III* (ChE 332 and ChE 333). Of the virtual laboratories, the content in the Virtual CVD Laboratory was new to students, but again was based on core conceptual knowledge. In contrast, slightly less than half of the students who completed the Virtual BioR Laboratory were concurrently taking *Bioreactors I* (BioE 457). Additionally, the industrial scaled processes upon which the virtual laboratories are based are considerably more complex than the physical laboratories.

The following is a brief description of the laboratories:

1. Ion Exchange - IX (3 weeks):
   Ion exchange is an important engineering process with a number of different applications, the most well-known of which is "water softening" or the removal of metals ("hardness") from aqueous streams. The Ion Exchange Laboratory consists of three components: building a standard curve to measure concentration of calcium, conducting a water softening experiment in a prototype system to capture calcium in a bed of Ion Exchange resin, then performing regeneration of the resin by passing a salt solution through the system. The standard curve for calcium is developed via drop-wise titration from an off-the-shelf aquarium water test kit. Water softening provides the opportunity to plumb the system and work with water flow and air bubble management. The regeneration process is straightforward experimentally and requires sample analysis by the Graduate Teaching Assistant.

2. Virtual Laboratory – VL (3 weeks)
   In a virtual laboratory, first-principles numerical simulations based on mathematical models implemented on a computer are used to replace the physical laboratory. However, rather than providing students access to the entire output of model, the output values are obscured by added noise, and provided to students only at the selected that they have decided to measure. The instructional design of the virtual laboratories is based on a cognitive apprenticeship model where students are provided a problem in a similar context to an engineer in industry. They provide a capstone experience in which students apply experimental design with a wider design space than is typically seen in the university laboratory. To be most successful, they must draw from both engineering science and statistics principles. Two virtual laboratories were used in Fall 2007 – The Virtual CVD Reactor and the Virtual Bioreactor.

   Virtual CVD Reactor. The laboratory team is tasked with developing a process "recipe" for high volume manufacturing of silicon nitride (Si_3N_4) using low pressure chemical vapor deposition (LPCVD) that grows Si_3N_4 to a target thickness of 750 Å uniformly within the wafer and from wafer to wafer. They also have access to a (virtual) ellipsometer, to measure film thickness at specified points on any wafer that they select. They are charged $5,000 for each run and $75 for each measurement (in virtual dollars).

   Virtual BioReactor . The laboratory team is tasked with developing optimal bioreactor operating conditions (i.e. choice of process parameters) for a bioreactor cultivation. Each team selected from two possible types of bioreactor applications: 1. production of a recombinant protein in yeast, and 2. degradation of a waste compound by a consortium of bacteria acclimated to the specific waste compound. The optimal conditions are defined as those that result in the highest volumetric productivity in the production of product or degradation of waste.

3. Heat Exchange - HX (2 weeks):
   Heat exchangers are a ubiquitous technology in the engineering fields. The Heat Exchange Laboratory provides students the opportunity to assemble and operate a double-pipe heat exchanger that uses a steam source (conventional kitchen pressure cooker) to heat water.

The students are responsible for performing a safety assessment, evaluating different plumbing configurations, performing heat exchanger performance calculations, and optimizing the process. The safety assessment requires the students to consider potential safety hazards such as thermal and electrical risks. The plumbing configuration options require thought about liquid and vapor flow, air accumulation, and heat transfer coefficient.

Method

A set of survey questions was posed to students in the CBEE 414 Senior Laboratory class in Fall 2007. The survey questions were asked after each of the three laboratories. The timing was, in general, as soon as possible after the final laboratory report for that given laboratory had been submitted. There were, in some cases, overlap with content presentation for the next laboratory. The following questions have been coded and analyzed:

1. What do you think the instructors intended you to learn by doing the (Ion Exchange/Virtual/Heat Exchange) laboratory?
2. How would you explain this laboratory experience to a first year student?
3. When you close your eyes and picture the lab experiment, what do you see?

The coding method for responses was developed as follows. The raw data were analyzed by content analysis to establish categories to group the responses.[22] An initial set of categories was identified by the principal investigator based on the focus of the research program on student cognition and the basic conditions of the laboratory experiences. An inductive set of codes was independently determined by the second researcher based on concepts that emerged from the first reading of the student survey responses. Coded sections of the survey from both researchers were compared to identify multiple common terms and few differences. The differences were discussed and reconciled. In addition, the course performance of students, measured by the final score on all assignments, was used to correlate aggregate responses to performance.

The number of coded statements in each category was summed across all of the student surveys for each of three researchers for each of the three laboratories. A single student response could be assigned to multiple categories. Interrater reliability was determined by comparing the code distributions in each of the coding categories. The intraclass correlation (ICC) was measured to be 0.78, 0.75 and 0.58 for the Ion Exchange, virtual and Heat Exchange laboratories, respectively. To improve the interrater reliability the process was modified as follows. The three researchers met together and the independently coded responses were compared and the differences reconciled. To determine the validity and reliability, two other researchers with no connection to the project were given a subset of the responses from one of the survey questions (20 responses per question per laboratory). This subset of responses was randomized among the three laboratories, so the researchers could not identify what response was associated with what laboratory. The two researchers went through the same process of individually answering and then reconciling the data. Values of interrater reliability for one of the questions, using the Cohen's Kappa (κ) statistic, are presented in Table 1. The overall values were 0.93, 0.85 and 0.89 for the Ion Exchange, virtual and Heat Exchange laboratories, respectively. This result indicates an improvement to a more reliable coding process. The fact that the second group had randomized responses suggests that there is not a bias based on the laboratory.

Table 1. Interrater reliability values for two groups of researchers in the consensus method used in this study

	Ion Exchange	Virtual Lab	Heat Exchange
Category 1	1.00	0.83	0.80
Category 2	*	0.88	*
Category 3	0.86	0.95	0.88
Category 4	*	0.89	0.95
Category 5	0.94	0.93	0.91
Overall	**0.93**	**0.85**	**0.89**

* The coefficient is not calculated since the coding of at least one group of raters is constant.

The number of student responses that were coded ranged from 43 to 46 for each of the three laboratories. With three reviewers coding each of three questions, there were a total of 1,191 individual coded responses in this study. In addition there were a set of 120 coded responses by two separate researchers to establish the reliability of the method. These results represent approximately 150 person hours of coding.

The data for each survey question were analyzed by summarizing each time a particular code was assigned to each student response resulting in a 0/1 pattern of data. Because the student responses were open-ended and the student responses were extended, multiple codes could be assigned to a single student response. Patterns of coded responses to the study questions were examined using a nonparametric analysis. While parametric techniques (such as the t-test) are more powerful than non-parametric techniques (such as the Kruskal-Wallis test used here), and are more likely to find a true relationship, parametric techniques make assumptions about the characteristics of the population from which the sample is drawn. For example, a conventional assumption is that the sample comes from a normally distributed population, an assumption that is violated with the student performance 0/1 data. The Kruskal-Wallis nonparametric test assumes only that the student performance data are ordinal and can be ranked for the three groups of students. However, the use of the Kruskal-Wallis non parametric test on this open-ended data with a small sample size increases the potential for a type 2 error to occur; specifically that true differences in student responses across the three laboratory experiences will be rejected when there are actual differences. The results and discussion sections should be read with that caution in mind.

Results and Discussion
The coding and analysis results from the three survey questions are presented below:

Question 1: What do you think the instructors intended you to learn by doing the (Ion Exchange/Virtual/Heat Exchange) laboratory?
Student responses for Question 1 were coded as 0/1 along seven categories where 1 indicates that the student response to the question included text that addressed the coding category and 0 indicates that the student made no reference to the concepts embodied by the code category. A description of the code categories is presented in Table 2.

Additionally, a qualitative judgment of the extent to which the response of the student invoked substantive cognitive processes was made based on the entire response by the student. Students were rated *Low* or *High* if they were believed to be exhibiting cognitive processes at the lower

Table 2. Categories for coding of survey Question 1.

Category	The instructor's intent was for the student to:
Understanding/Critical thinking	Develop higher level critical and creative thinking and understanding in a general sense (i.e., useful to other experiments and experiences).
Lab Protocol/Skills	Develop specific techniques and skills of hands on experimental work, encounter concepts in a hands-on environment, or address safety issues. This category is only marked when the student is specific.
Experimental Design	Learn the nature of designing experiments including the process of identifying the problem, designing the data collection method to address the problem, analyzing the results and making decisions. A low level response to this simply identified experimental design as an outcome.
Situated Nature	Place the laboratory experiment in the context of their future professional environments or scenarios.
Communication/Documentation (Comm/Doc).	Develop written and oral communication skills and practice report writing, including reporting results to clients.
Specific Content (literal)	Learn the specific topics or content within the laboratory assignment or reinforce understanding of content learned in lecture classes (e.g., resin capacity in ion exchange).
Team Skills	Learn how to work effectively with others as part of a team.

level or higher level, respectively. For example, a student response could be assigned to a low level when it only referred explicitly to 'experiment' or 'experimental design.' Conversely, student responses were assigned to a high level when they referred explicitly to the multiple steps that they had to take to determine how to determine the response to the question posed by the laboratory or if the student referenced the use of conceptual knowledge together with problem-solving or experimental design processes. The following response is an example of one that was rated as High by the three researchers:

> I believe that the virtual lab was intended to simulate a complicated process where one could perform many more experiments than if it were a real lab. It was focused on the analysis and synthesis aspects of understanding because the data was easily obtained but the real question was what does it mean about the input parameters and how should it direct further testing.

A response rated as Low by all researchers is:

> The objective was to learn to work effectively as a team, and to design an experiment where optimization is essential.

A plot of the percentage of responses rated as High Cognition and the percentage of responses in each category for each laboratory is shown in Figure 2.

A parametric statistical analysis of the student responses to Question 1 among the three laboratories showed statistically significant differences on the categories of Cognition and Critical Thinking. Given the nature of the data, a non-parametric analysis was conducted that could not find these differences in these categories. This issue should be considered in the following interpretations of the data. The non-parametric analysis shows evidence of statistically significant differences between the responses of the students to the questions asked following the different laboratory experiences in the following categories:
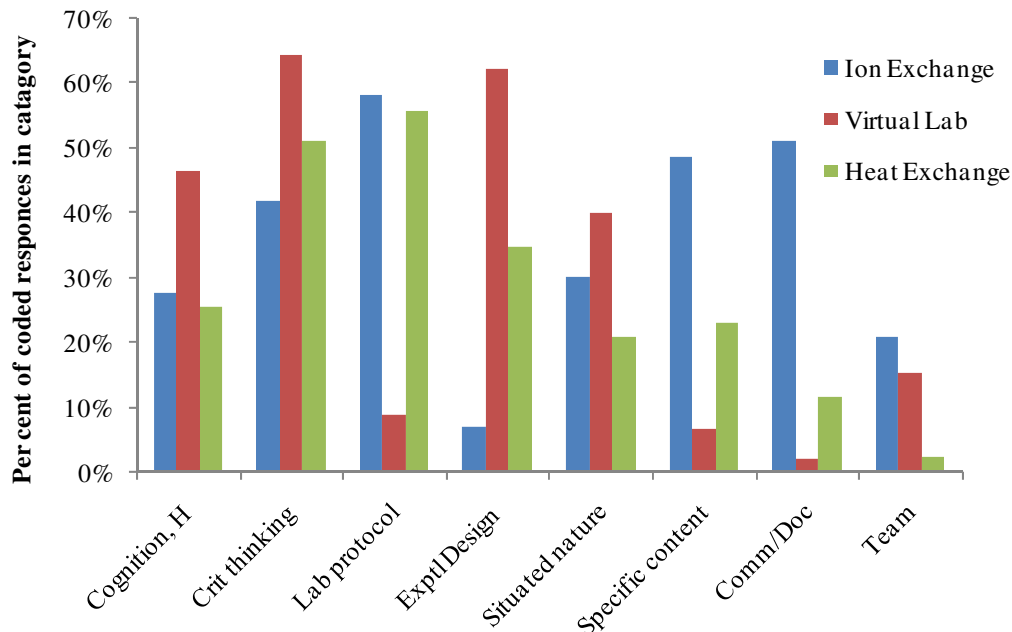
Figure 1. Summary of students' perception of instructor's intent (Question 1) by category. A single student's response could indicate several categories.

- Lab Protocol / Skills (p < 0.05, Kruskal Wallis H = 28.2, df = 2)
- Experimental Design (p < 0.05, Kruskal Wallis H = 29.2, df = 2)
- Specific Content / Literal (p<0.05, Kruskal Wallis H = 20.4, df = 2)
- Communication/Documentation (p < 0.05, Kruskal Wallis H = 34.7, df = 2)
- Team (p < 0.05, Kruskal Wallis H = 6.94, df = 2)

The Critical Thinking category is ranked higher in the virtual laboratories than in the physical laboratories (64% vs. 42 and 51%). Again, this increase is consistent with the premise that the virtual laboratories promote high level cognition. Similarly, the statements that were coded as Experimental Design averages 62% for the virtual laboratory. This value is significantly higher than the first physical laboratory which averages 7%. This result is consistent with the instructional design of the virtual laboratories, which, in part, is to engage students in an iterative experimental design approach that is reflective of the approach used by practicing engineers.[2] Indeed, a significant portion of instruction was devoted to explaining this context. However, there is also a significant improvement in awareness of experimental design from first physical laboratory to second physical laboratory (35%). It is not certain whether students are carrying their awareness gained from their experience in the virtual laboratory back to the physical laboratory or if some other factor is contributing. In contrast, the Lab Protocol/Skills are the highest rated in physical laboratories while insignificant in the virtual laboratory (52 and 51% vs. 3%). This result is consistent with the notion that the physical laboratories play an important role in developing haptic skills. Finally, Communication/Documentation is significantly higher in the first physical laboratory than the virtual laboratory and the second physical laboratory. It is believed that this result the students becoming acclimated to the writing expectations in this course.

The percentage of high cognition statements is approximately double in the virtual laboratory (47% vs. 28% and 26%). Previous research has demonstrated the Virtual CVD Laboratory promotes high level cognition.[23] The coded student responses were correlated to student performance in the class. Figure 2 shows a plot of the aggregate normalized score vs. the number of high cognition statements (Hs) a student had in total for all three laboratories. For example, the final class grade of the group of students who did not receive a single H ranking (Number of Hs = 0), was averaged subtracted from the entire class' average and divided by the standard deviation. This resulted in a value of -0.29. The score improves with number of high cognition statements from 0 – 2. This result indicates that, in this case, what students understand about the goals and objectives of their learning experiences does correlate to their performance. There also appears to be a saturation effect at high values of Hs.
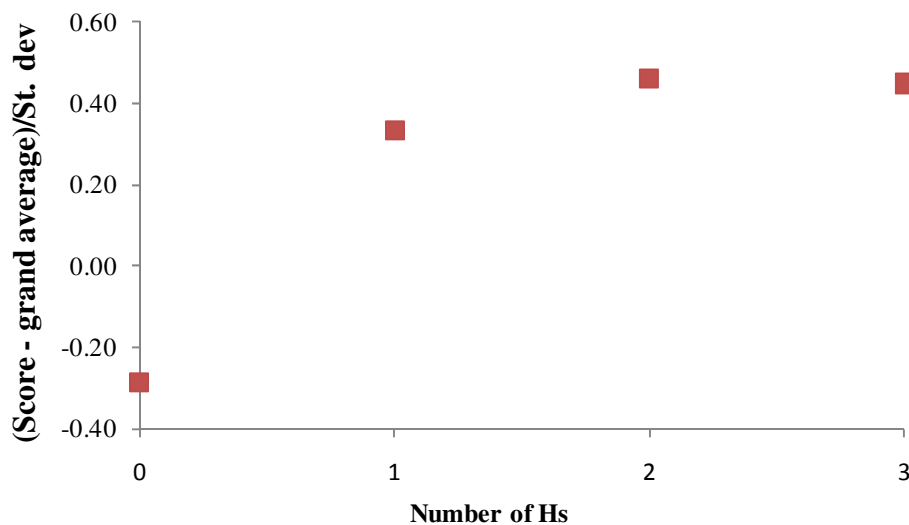
Figure 2. The relationship between the number of a student's responses (a possible of three, one for each lab) that exhibit higher level cognitive processes on Question 1 and his or her overall normalized score in the course.

Question 2: How would you explain this laboratory experience to a first year student?
Student responses for Question 2 were coded as 0/1 along eight categories. A description of the code categories is shown in Table 3. A plot of the percentage of responses in each category for each laboratory is shown in Figure 3. Students' statements in response to this question from the three laboratory experiences are statistically different on four of the eight categories used in coding Question 2 as follows:

- Experimental Design ($p < 0.05$, Kruskai Wallis H = 30.9, df = 2),
- Ambiguity ($p < 0.05$, Kruskai Wallis H = 18.6, df = 2),
- Conceptual ($p < 0.05$, Kruskai Wallis H = 7.7, df = 2), and
- Lab protocol/Skills ($p < 0.05$, Kruskai Wallis H = 7.7, df = 2),

Though there are statistically significant differences in the student responses on the four categories, the effect sizes for the significance of the relationship between the students'

responses in each laboratory category were moderate or low. This result can be expected from the open-ended nature of the survey design. The open-endedness was intended to elicit a variety of responses, and, therefore, frame a richer picture of the students' perceptions of the laboratory experiences. However, this approach resulted in relatively low numbers of responses that were coded as addressing a particular category.

Table 3. Categories for coding of survey Question 2.

Category	The senior laboratory was described by:
Experimental Design	Learning the nature of designing experiments including the process of identifying the problem, designing the data collection method to address the problem, analyzing the results and making decisions.
Achievement	How the first year student can succeed or earn a good grade.
Ambiguity	The ambiguous or open ended nature of the experience or how the need to adaptively learn.
Conceptual	The concepts in the curriculum that the laboratory reinforces.
Situated Nature (Real World)	Placing the experiment in the context of future professional environments or scenarios.
Specific Content (literal)	Learning the specific topics or content within that laboratory assignment (e.g., resin capacity in ion exchange).
Lab Protocol/Skills	The development of specific techniques and skills of hands on experimental work. This category is only marked when the student is specific.
Communication/Documentation (Comm/Doc).	The development of written and oral communication skills.
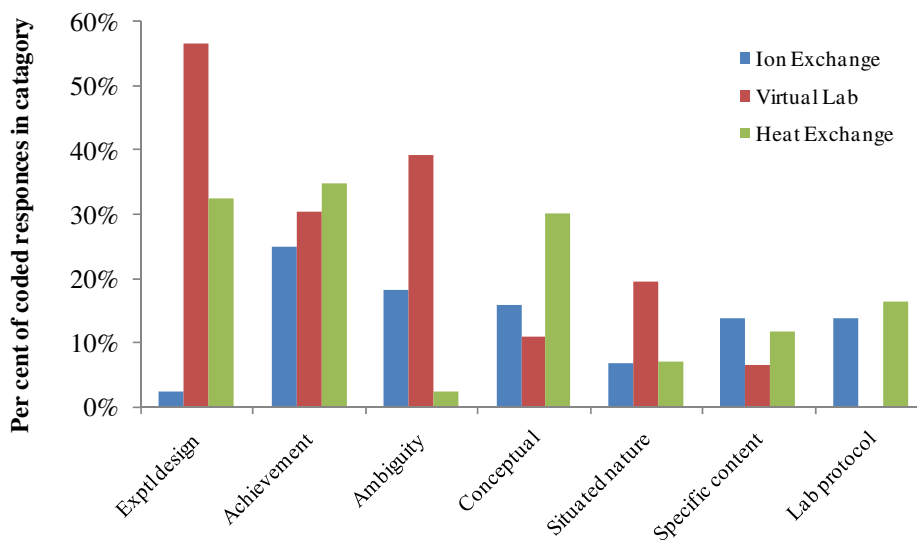
Figure 3. Summary of how students would explain each laboratory to a first year student (Question 2) by category. A single student's response could indicate several categories.

Differences were found between the student responses in all 3 laboratories on the Experimental Design category of Question 2. Fifty-seven percent of the student responses in the virtual laboratory addressed the Experimental Design category compared with 33 percent of the students in Heat Exchange laboratory ($p < 0.025$, Mann Whitney U = 752.0, Z = -2.3) and 2 percent of the students in the Ion Exchange laboratory ($p < 0.025$, Mann Whitney U = 659.0, Z = -3.7). The

difference in responses between the students in the virtual laboratory and Heat Exchange laboratory (r = 0.24) was found to be weak and the difference between the students in the Heat Exchange laboratory and the Ion Exchange laboratory (r = 0.40) was found to be moderate. Similarly, differences were found between the responses of students in all 3 laboratories on the Ambiguity category. Thirty-nine percent of the student responses in the virtual laboratory addressed the Ambiguity category compared with 18 percent of the students in Ion Exchange laboratory (p < 0.025, Mann Whitney U = 800.0, Z = -2.2). This difference was weak (r = 0.23). Eighteen percent of students in the Ion Exchange laboratory demonstrated an understanding of the Ambiguity category compared with 1 percent of the students in the Heat Exchange laboratory (p < 0.025, Mann Whitney U = 796.0, Z = -2.4). The differences in responses was weak (r = 0.26). It was not possible to determine the specific differences between the performance of students from the different laboratories on the Conceptual category, as too few student responses were coded by this category. References to the laboratory protocol are significantly lower in the student responses to the virtual laboratory than to the Ion Exchange laboratory or the Heat Exchange laboratory. As Figure 2 illustrates, none of the 46 students in the virtual laboratory made references to the Lab Protocol as an explanation of the laboratory experience compared with 14 percent of the students (6 of 44) in the Ion Exchange laboratory, the set of responses from the laboratory experience that is the nearest other group (p < 0.025, Mann Whitney U = 874.0, Z = -2.6). The differences in responses was weak (r = 0.272). No statistically significant differences were found between the students' performance in the Ion Exchange laboratory and the Heat Exchange laboratory.

Approximately one-fifth of the student responses in the first physical laboratory were coded with Ambiguity. This result is consistent with the learning objectives of this relatively more open-ended laboratory course, and where it is placed in the curriculum. However, there is a statistically significant increase in this category for the virtual laboratories. This result is also expected, based on the instructional design of the virtual laboratories, which, in part, is to promote a learner-centered approach to an open-ended design problem which results in an increase in the student's tolerance for ambiguity.[23] Correspondingly, only one student response in the next physical laboratory, the Heat Exchange laboratory was rated as ambiguous. While a component of this result can be attributed to the student's greater familiarity with the content in the Heat Exchange Laboratory, it is also believed that the virtual laboratory experience gives them a perspective that makes the physical laboratories appear less ill-structured. A look at specific student responses supports this belief. A typical statement for the Ion Exchange laboratory is as follows:

> I would tell them that this was not the best lab experience. I felt that the instructor was not always clear with he wanted from us. But I would also tell them that this made us think about what we were doing. When there were sections of the procedure that did not make sense it required you to think about what needed to be done. This was usefull (sic) because much of the time in labs all that is required is to follow a procedure like a robot which is something anyone can do.

Most of the statements from this laboratory echoed the lack of clarity of instruction. The student responses for the virtual laboratory demonstrate a different perspective. For example consider the responses:

> The virtual lab is an exercise in being the professor. Instead of being the one to run an experiment and interpret the results, you have to design an experiment that will give the appropriate results. The

emphasis of the virtual lab is not how to run different experiments, but rather how to decide what experiments to run. Consequently there is no "right" answer. Any experiments run that yield more knowledge about the process are good experiments.

and:

> The first two thirds of it are confusing and a bit of a struggle. It is sometimes unclear exactly what is going on and then suddenly it clicks, and you figure it out and it all comes together. Advice: Know your objectives before you start doing runs! Analyze data as you go so you know whether or not you are successful in early runs, and don't be set on one approach - be willing to adjust your experimental design.

Both these latter responses indicate ambiguity; however, there is a clear shift from an ambiguity in the instruction and instructors' expectations to an ambiguity in the experimental process itself.

While only one response was coded for Experimental Design in the Ion Exchange Laboratory, 57% of the responses from the virtual laboratories indicated this category. Additionally, there was an increase in responses for the second physical laboratory (33%) in comparison to the first, indicating an awareness to experimental design. These results are consistent with those discussed with Question 1 (Figure 1). While the responses towards Experimental Design increased in the physical laboratory following the virtual laboratory, the opposite is seen for Ambiguity. In other words, it may be conjectured that students are learning about experimental design and learning how to better tolerate ambiguity.

There were no significant differences among the students' responses that addressed the Achievement category. Fourteen percent of the students' responses were coded as providing information about how to succeed or get a good grade in the laboratory in the virtual laboratory compared with 11 percent of the students in the Ion Exchange laboratory and 15 percent in the Heat Exchange laboratory. This result supports the interpretation of achievement as a more personal and internal factor that is relatively uninfluenced by the laboratory context.

Question 3: When you close your eyes and picture the lab experiment, what do you see?
Student responses for Question 3 were coded as 0/1 along five categories. A description of the code categories is shown in Table 4.

Table 4. Categories for coding of survey Question 3.

Category	The student describes seeing:
Physical System	Physical elements of the system such as the ion exchange column or the chemical vapor deposition furnace.
Computer Interface	The computer interface in the virtual laboratory.
Representation/ conceptual	Representation of the concepts in the laboratories such as ions exchanging on the resin bead or cells growing in medium and 'eating' waste.
Cognitive Activities	Representation of cognitive activities such as developing equations to describe the behavior of the system, analyzing the data on their excel spreadsheet, or themselves thinking about the processes.
Human Interaction	Examples of human interaction such as team members discussing the projects such as the instructor helping them to trouble shoot the system.

A plot of the percentage of responses in each category for each laboratory is shown in Figure 4. There is evidence of differences between students from the different laboratories on in their responses on three of the five categories used in Question 3 as follows:

- Physical System ($p < 0.05$, Kruskai Wallis H = 20.0, df = 2)
- Cognitive ($p < 0.05$, Kruskai Wallis H = 13.0, df = 2).

Since two of the three laboratories in the Computer Interface category had no response, statistics for this category were not calculated.
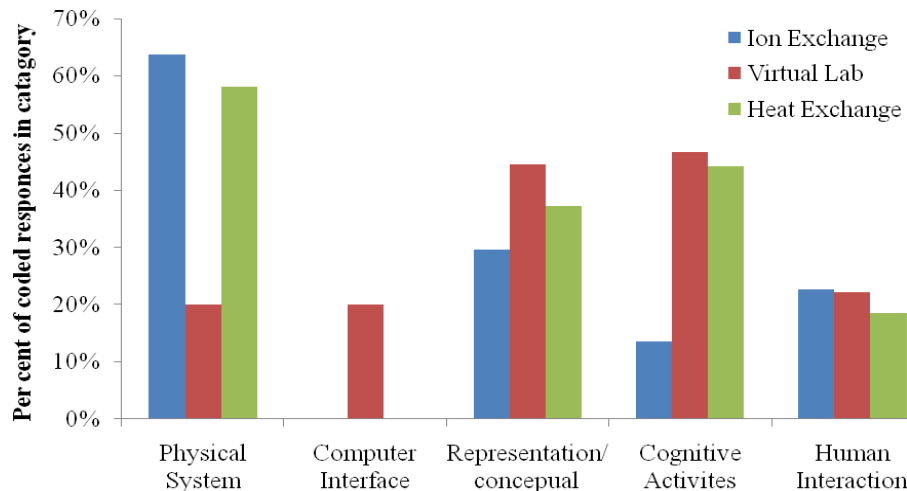
Figure 4. Summary of students' responses to Question 3 (When you close your eyes and picture the lab experiment, what do you see?) by category. A single student's response could indicate several categories.

As Figure 4 illustrates, only 20 percent of the students' responses to Question 3 in the virtual laboratory (9 of 45) addressed the Physical System compared with 58 percent of the students in the Heat Exchange laboratory, the nearest other group (25 of 43) ($p < 0.025$, Mann Whitney U = 598.5, Z = -3.7). The relationship between students in the virtual and Heat Exchange laboratories and their responses on the physical category was found to be relatively weak ($r = 0.39$). No differences were found between the responses of students in the Heat Exchange laboratory and the responses of students in the Ion Exchange laboratory on the Physical System category. Only 14 percent of the students' responses to Question 3 in the Ion Exchange laboratory (6 of 44) addressed the Cognitive Activities category compared with 43 percent of the students in the Heat Exchange laboratory (19 of 44) ($p < 0.025$, Mann Whitney U = 657.0, Z=-3.13). The relationship was found to be moderate ($r = 0.34$). No differences were found between the responses of students in the Heat Exchange laboratory and the responses of students in the virtual laboratory on the cognitive category.

A key issue in virtual laboratories is the authenticity of the learning experience. There is a danger that students disengage from connecting to the underlying process being simulated, and instead transition into a *computer game* mode. Whether the students are maintaining a reality focus is an important aspect of how they construct their learning within the laboratory, and as

such can potentially alter the overall learning outcomes of the experience. While students strongly associated both physical laboratories to the physical system, the same is not true of the virtual laboratory experience. In the virtual environment, students were just as likely to envision the computer interface as the physical system, and were more likely to answer this question in some other context. Clearly, this aspect of this experience can be improved. There are two components to improving this perception. One is the reality presented through the animations in the software. This aspect is labor intensive to change. Another component is the laboratory culture established by the assignments and the social interactions with instructors and peers. An important consideration in instructional design and in instructor scaffolding as others adopt this method is ways to create a laboratory culture that positively reinforces the authenticity of the process.

Both Questions 2 and 3 indicate a low reference to thinking or reasoning about solutions to the problem posed by the Ion Exchange laboratory as compared to the Heat Exchange laboratory. This result is interesting considering the familiarity with the processes from the required prior coursework. Students are relatively unfamiliar with the ion exchange process, but have broad exposure to Heat Exchange. It may be that the newness of ion exchange requires such a large cognitive load that students focus on the physical equipment more than the conceptual context. Being more familiar with the process of heat exchange gives them a mental framework to facilitate conceptual understanding. While this result is speculative, and requires more careful study, it does suggest that laboratories are not best used for learning new content but rather for constructing new knowledge from somewhat familiar content. On the other hand the virtual laboratory presented many students with relatively new conceptual and experiential contexts, but students were able to engage on a conceptual level. This result is consistent with data from *protocol analysis* which suggests that the virtual laboratory lowers cognitive load relative to a physical laboratory and frees students to focus on other aspects of learning.[2]

Conclusion
An analysis of student survey responses after they have completed each of three laboratory experiences has been conducted. The first and third laboratories are physical laboratories, based on the unit processes of ion exchange and heat exchange. The second is a virtual laboratory. The study presented in this paper seeks to identify the ways that student knowledge and awareness of their own learning compares as they complete these three laboratories. A coding method has been developed which demonstrated an interrater reliability of 0.9 and suggests that there is not a bias based on the laboratory. Analysis of metacognitive statements of students show enhanced awareness of experimental design, and greater occurrences of critical thinking and higher order cognition in the virtual laboratory, and an enhanced awareness of laboratory protocol in the physical laboratories. The number of high cognition statements correlated with student overall performance in the course. Additionally, there is a shift from a perception of ambiguity in the instruction and instructors' expectations to an ambiguity in the experimental process itself. However, there is indication that a significant portion of students may not view the virtual laboratory as a real system. Finally, the non parametric statistical tests used to analyze these open-ended data increase the potential for a type 2 error to occur; therefore, we intend to repeat this analysis in future years to increase the sample size.

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