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Designing Blended Inquiry Learning in a Laboratory Context: A Study of Incorporating Hands-On and Virtual Laboratories

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Abstract This article reports on the development of a methodology that integrates virtual and hands-on inquiry in a freshman introductory biology course. Using a two time×two order-condition design, an effective combination (blend) of the two environments was evaluated with 39 freshman biology participants. The quantitative results documented no significant effect of presentation order but demonstrated a significant effect of the combined learning experience. The qualitative results showed a strong preference by students for the virtual work preceding the hands-on laboratory. The study provides practitioners an effective alternative to traditional instructional practices by combining virtual and hands-on inquiry learning.

Key words inquiry learning · virtual laboratories · biotechnology teaching · science education

In many of the higher education disciplines, and specifically in the natural sciences, technological advances require ongoing innovation for the preparation of future

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professionals. Recent reports indicate the need to strengthen our higher education infrastructure, especially in the preparation of science, technology, engineering, and mathematics students, in order to be competitive in the world (National Science Foundation 2007). Fueled by the recent increase in biotechnology job opportunities, there is specific interest for innovation in the teaching of biotechnology and molecular biology concepts. DNA-based techniques are now commonly used in scientific laboratories to investigate the genetic profile found in a crime scene, to document the relatedness of different species, and to verify identity and paternity. These scientific advances are now routinely applied in medicine to determine genetic conditions and to aid in the diagnosis of diseases. Consequently, biotechnology is a topic of interest for the scientifically literate citizen, and it is appropriate content for both biology majors and non-majors (Kerfeld et al. 2001). A fundamental methodology in biotechnology applications is DNA gel electrophoresis: the separation of negatively charged DNA fragments by size in a porous medium (an agarose gel), under electric current. Accordingly, there is an increased desire to teach gel electrophoresis in the biology laboratories of higher education institutions. To this end, a variety of commercial laboratory suppliers provide easy-to-follow, protocol-based kits of reagents and equipment. While these packages are excellent for complex experiences in real-world processes, they are oriented to replicate a scientific protocol in a step-by-step manner rather than supporting students' active, inquiry-based discovery. As a result, the overuse of these materials may reduce the potential of inquiry learning—the methodological essence of scientific discovery.

Inquiry learning, as a methodology to incorporate real-world learning, has been applied in various disciplines in higher education (Fortus et al. 2006; Garrison and Kanuka 2004; Justice et al. 2007). In light of these issues, our efforts focused on developing a pedagogy that preserves the beneficial aspects of hands-on laboratory work while extending it with deeper, inquiry learning made possible by the use of technological tools. While all higher education science instructors are painfully aware that inquiry learning is time consuming and resource-intensive, a current innovation is to blend hands-on and on-line learning environments (Garrison and Kanuka 2004), using the benefit of modern technologies to ease this burden. Virtual laboratories are software tools that allow the user to conduct the same scientific inquiry afforded by hands-on investigation but at a reduced expense, with increased safety, and within the time constraints of higher education classrooms. However, the instructional application of virtual laboratories is often based on trial and error, fueled by perceptual features rather than the instructional objectives set forth. In this article, we discuss a research-based methodology of inquiry teaching in which we do not "select the cooking pots and pans until (we) have planned the menu" (Morris 2006, p. 2). To this end, we discuss the key processes of our instructional design (objectives, activities, and assessments) for the integration of a hands-on laboratory and a virtual laboratory in a blended inquiry environment. The theoretical grounding for the study stems from two fields indicating the complexities of learning science via authentic inquiry and the opportunities software tools, such as virtual laboratories, may provide.

Theoretical Grounding

Prior studies of the processes of inquiry learning in science and of the integration of technological tools during inquiry learning provided the theoretical and empirical grounding for this study.

Recent Research on Inquiry Learning

The National Research Council [NRC] (2000) defined inquiry as incorporating the complex processes of asking questions, using evidence to respond to questions, formulating explanations using evidence, connecting new explanations to prior scientific knowledge, and communicating explanations and justifications to peers (National Research Council 2000, Tables II–VI, p. 29). These steps highlight a constructivist perspective of learning by illustrating the purposeful, active construction of knowledge during inquiry. This perspective of inquiry as a methodology to construct scientific knowledge combined with prior conceptualizations of inquiry as a methodology for teaching (Justice et al. 2007) contributed to our inquiry learning strategy and informed our instructional design.

We followed a classical model from the cognitive psychology literature and categorized the phases of problem-solving during scientific inquiry as *searching* the task environment, *evaluating* data results, and *reasoning* by mapping knowledge to prior understanding (Fay and Klahr 1996). We used these three phases to examine prior research on science teaching processes and found two different perspectives on the practical implementation for inquiry learning. One perspective suggests that the best way to teach scientific inquiry is by providing students authentic experiences that resemble the real-world environment of scientific laboratories (Roth 1995). Another perspective focuses on the practical constraints of classroom environments and suggests the incremental assistance of students' inquiry learning expertise (Bell et al. 2005; Rezba et al. 1999). This second perspective is supported by numerous studies illustrating students' difficulties during inquiry learning. For example, in science settings students have difficulties with scientifically controlling experiments, may use biased interpretation of empirical data, and often formulate inappropriate inferences to explain the results of inquiry (Chen and Klahr 1999; Kozlowski 1996; Toth et al. 2002). Furthermore, our own teaching experiences had made us aware of procedural and conceptual errors common among college students during hands-on gel electrophoresis. These procedural errors include incorrect gel loading techniques (primarily puncturing gel wells) and common conceptual errors such as students' misconception of polarity (the charge of the DNA molecule) and the logical setup of the equipment to allow DNA fragment migration towards the positive pole. These errors pose considerable challenges during the practical implementation of hands-on gel electrophoresis. Our approach to solve these problems was to integrate a virtual laboratory with a hands-on laboratory. In essence, our instructional design aimed to find an effective pedagogy that reduces the cognitive demand on students while also providing them the opportunities for essential learning in complex, error-prone, hands-on environments (Toth and Klahr 1999, 2000). The specific characteristics of the two environments are compared and contrasted in the methodology section. Here, we continue the theoretical grounding of the study by exploring prior research on how (and whether) technology tools can support inquiry learning.

Inquiry Learning with Modern Technologies

Prior studies offer evidence that software-supported learning environments allow users to focus on authentic science, make improved predictions by way of instant feedback on data manipulations, and develop accurate mental models of phenomena (e.g. Monaghan and Clement 1999; Zaharia and Anderson 2003). Contradictory to these studies, however, are results indicating that software-supported learning environments may undermine the instructional goal of inquiry and debate due to a perceived authority of technology (Waight

and Abd-El-Khalick 2007). Software tools may also focus attention on surface, perceptual features and thus hinder reflection leading towards complex knowledge construction (Olson and Clough 2001). As with many other instructional methods, students with considerable prior knowledge may be at advantage to learn more with technological tools (Winn et al. 2006). While research has examined the effects of different instructional strategies to overcome students' difficulties with inquiry (Toth et al. 2000) and specifically the development of pedagogies for inquiry learning with technological tools (Toth 2009), the contradictory findings on effectiveness require the further examination of design decisions.

The recent development of design principles for educational software tools, including virtual laboratories (Quintana et al. 2004), provided clarity and guidance for our instructional design to integrate virtual laboratories and hands-on laboratories for inquiry learning. For example, we used a virtual laboratory tool with the purpose of automating routine tasks and reducing the cognitive demands of authentic inquiry. We also used personally relevant examples for students so as to elicit attention and motivate students for active learning. In our instructional design we considered the additional data representation available in the virtual laboratory of our choice while also raising awareness about experimental error that can occur during hands-on laboratory work. With these considerations, we sought to answer two research questions.

Research Questions

The two research questions of this study examined students' "end-state" knowledge (before and after inquiry) and documented students' individual experiences and attitude toward the blended inquiry environment. The research questions were as follows:

- Which order-condition is more beneficial for students' knowledge development during inquiry learning when possible differences in prior knowledge are controlled? We hypothesized that there will be no significant difference in students' learning due to order-condition because the integration of the two environments provides the same overall learning opportunities.
- What are students' self-reported experiences about the benefits and disadvantages of working with the two learning environments? Using qualitative analysis we anticipated gaining information that would corroborate the quantitative findings and provide additional detail on students' learning with the two environments.

Methodology and the Study

The Pedagogical Approach

The curriculum unit was designed to coordinate the key elements of instructional design: the goal of instruction, the activities to achieve these goals, and the methods of assessment. The assessments are described in the methodology section. In explaining our research-based instructional approach here, our hope is that classroom practitioners will be able to adapt it for their own classrooms.

Within the domain of DNA gel electrophoresis, the *goal of instruction* was for students to be able (1) to search the task environment by creating multiple, scientifically controlled experiments, (2) to evaluate data results by measuring the effects of variables and by determining the effects of these based on the outcome data, and (3) to apply this newly

synthesized knowledge to reason about the mechanisms of the outcome in real-life problem solving situations. That is, the aim was for students to employ inquiry learning in order to understand key concepts of gel electrophoresis. This routine methodology in scientific laboratories is facilitated by the innate characteristics of the DNA molecule. The inherently negative DNA molecule migrates to the positive pole in an electrophoresis unit under current over a porous medium (agarose gel) that allows the differential movement of DNA fragments. As the DNA travels to the positive pole, fragments of different lengths will migrate according to size as the porous medium behaves as a molecular sieve. This differential movement of variable sized DNA fragments creates a distribution that is unique to an individual, proving useful in genetic identification and paternity testing. Due to the fundamental nature of this methodology, it is imperative that students gain a thorough understanding of the process as well as the variables that influence the outcome of the process.

As part of the *learning activity* we used a problem-solving scenario to place students' inquiry into an actual laboratory setting where they had to determine the role of concentration and voltage on the distance DNA fragments travel. An additional problem-solving scenario was included during the hands-on laboratory to apply electrophoresis results to solve a crime. Students' activity included the use of two different environments during the blended inquiry task: a virtual laboratory (VRL) environment and a hands-on laboratory (HOL).

Work with the VRL environment During work with the VRL, groups of students collaborated in the computer laboratory and designed as many experiments as they were able to complete in one hour. The VRL employed in the study (MyDNA 2003) supports inquiry learning as an alternative to providing a ready-made protocol for students to follow. With this VRL users can design experiments by modifying gel concentration and voltage values—two pivotal variables that influence the gel electrophoresis outcome—to search the task environment. As the concentration of the gel increases, larger DNA bands are retained in the gel. Similarly, an increase in voltage allows for faster fragment migration due to the higher electrical output. The point-and-click interface of the VRL automates the routine task of creating solutions and agarose gels while preserving the essence of inquiry learning. In addition, the VRL focuses students' learning on the specific mechanisms of the gel electrophoresis process by providing a visual illustration of how the different sized DNA-fragments (small, medium and large) travel based on their size from the original loading point towards the positive pole. This visual representation is not available during the hands-on laboratory, where only the end-state of DNA fragment distribution is revealed. One simplification that the VRL makes to assist students in their early experimentation is to eliminate the potential of the error of not stopping the process in time—an error that can result in the DNA fragments "running off" the gel into the electrophoresis chamber. If students do not stop the experiment in the VRL, the process halts automatically when the smallest bands reach the end of the gel. While this process significantly reduces the cognitive load on students, the results of the study will illustrate some problems we encountered with this automation. These considerations will undoubtedly enter into practitioners' instructional design decisions for the integration of this VRL with a HOL.

Work with the HOL environment The basis of the laboratory work was a commercially available kit that provided DNA samples from a hypothetical "crime scene" and the DNA from several "suspects". These samples had to be separated via gel electrophoresis so as to suggest whose DNA was at the crime scene. To do so, students were divided into groups

working around three lab benches equipped with four electrophoresis units, reagents, power supplies, and a set of pipettes to load samples. To design experiments, students could select from pre-cast agarose gels in three different concentrations (0.6%, 1.2%, and 2.0%), similar to their work with the VRL. The range of voltage was, however, slightly altered from that provided by the VRL due to practical constraints although the concept of voltage value selection was congruent with the VRL. Due to the time constraints and the limited equipment in the hands-on setting, students had to share equipment and collaborate on the interpretation of results with other groups. Thus the group work with the HOL resembled that with the VRL, and students kept to the same groups while working in both environments. After choosing four gels per bench, the students placed each gel into an electrophoresis unit, set the voltage, and ran the experiment for one hour.

Comparison of Activities with the VRL and the HOL In addition to our practical and instructional focus, our research aimed to document students' learning in the two environments. Thus, Table I compares and contrasts the specific activities with the two environments in relation to the instructional objectives. Both environments equally

Table I Comparison of Students' Activities with the Two Environments in Coordination with the Three Learning Objectives for Scientific Inquiry

Objectives	Component Activities	Application of HOL	Application of VRL
Search phase			
Students will be able to create multiple, scientifically controlled experiments	Set up gel electrophoreses	Physical setup of electrophoresis unit and manual sample loading	Automated setup of electrophoresis unit and sample loading
	Design experiments	Select ready made gels to design hands-on tests	Automated request for new gels (point-and-click)
	Examine multiple variables with design	Select pre-cast gels with different concentrations, and select a voltage from a range	Point-and-click to select gel-concentration and voltage values from a range
Evaluation phase			
Students will be able to measuring the effects of variables and determine the direction of their effects	Measure distance traveled in response to variable settings	Use commercially available DNA-ladder with known fragment sizes	Use a ruler or estimate the proportion of distance traveled
	Evaluate the direction of effects	Concentration is inversely proportional with distance. Voltage is linearly proportional to distance	Concentration is inversely proportional with distance. Possible error of automation for voltage effect
Reasoning phase			
Students will be able to reason about the mechanisms of the outcome in real-life problem solving situations.	Reason for the mechanisms of effects	Reason about the end-state of DNA movement—poor visibility on a real gel	Reason about the end-state of DNA movement—with visual support for process
	Apply reasoning to solve a real-life problem	Scientific reasoning about variable effects on distance. Practical reasoning about fragment distribution	Scientific reasoning about variable effects on distance. No practical reasoning

supported the *search* phase and experimental design activities with either the physical setup of variables in the hands-on apparatus or with a point-and-click interface of the VRL. Accordingly, students were able to practice manual skills such as loading DNA samples with the HOL while formulating repeated experiments in a short amount of time with the automated setup of the VRL. To design experiments with a range of concentration values students choose ready-made gels in the HOL environment or used the point-and-click interface of the VRL. Similarly voltage values were selected with the physical equipment within the range provided by the instructor (80–120 V) or selected from a range provided by the VRL (5–50 V).

In the *evaluation* phase the VRL did not provide any measurement instruments, so students could choose to either estimate the distance traveled as a proportion compared to the starting position or use a ruler. The hands-on investigation used a DNA-ruler (a sample with DNA fragments of pre-determined lengths which was loaded into one well on each gel). Students then had to evaluate the effect of each variable (concentration and voltage) based on their measured outcome. A difference in the two approaches was that the hands-on investigation required students to stop the process at a certain running time (60 minutes) whereas the VRL attempted to avoid a possible error in this step and was programmed to stop when the small fragments reached the end of the gel. The students' assignment was to use discussion to resolve the possible cognitive conflict that may have resulted from this simplification in the VRL as compared to the results of the hands-on environment.

Our instructional design provided two slightly different *reasoning* experiences for students. One type of reasoning focused on the relationship between fragment length and distance traveled, or the "mechanism" by which the variables contribute to the outcome. Both environments provided a chance for this reasoning by illustrating the end-state distribution of DNA fragments based on their size. However, the VRL provided an additional representation (a short animation) to illustrate how the bands actually migrated based on the size, whereas the HOL only focused on the end-state distribution. We refer to the process of determining the effects of variables as "scientific reasoning" (Table I) because it focuses on the scientific relationship that produces the outcome results. Another type of reasoning we employed focused students on the application of their scientific understanding for crime scene problem-solving by examining a DNA fingerprint and determining a match between two DNA distributions to rule out a suspect. This type of reasoning is different than the focus on variable effects leading to an outcome distribution; thus we refer to this type of reasoning as "practical reasoning" (Table I). The last component of instructional design, the measurement of students' learning, is described in the next section along with the experimental design, protocol, and the results for students' learning.

The Study Design

The study employed a two time (pre- and post-inquiry) × two order conditions (VRL-first or HOL-first) quasi-experimental design. One group of the students used VRL first followed by the HOL, and the other group started their learning with the HOL followed by the use of the VRL. Following Cook and Campbell (1979) we refer to the design as "quasi experimental" despite the fact that the assignments of students to the two different sections of the course (the different comparison groups: VRL-first and HOL-first) were randomly administered by the normal registration process. Other than the order of using the two inquiry environments, the two classrooms were not significantly different in their ability, socio-economic background, or gender-distribution. However, the circumstances of this classroom study did not allow for a fully controlled and randomized design. Students performed all inquiry tasks in groups and documented their learning

on individual pre- and post-tests. With this design, the study measured students' "end-state" knowledge (their knowledge before and after inquiry learning) as well as their self-reported problems during their move between the virtual and hands-on investigation. The study was directed by the first author who was a participant observer during the class and implemented by the second author with collaboration with the third author during the instructional design process.

Participants

College students from an inner-city, private university in a medium-sized city in the U.S.A. participated in the study. This is a medium-sized, Catholic university with a current enrollment of about 10,000 students. Biological Inquiry is a freshman-level introductory course which includes both a lecture and a laboratory component. The purpose of the course is to provide students with a knowledge base of biochemistry, molecular biology, genetics, and development. The goal of the course is to inspire critical thinking and the application of knowledge during practice-focused, hands-on laboratory activities. The course is filled by invitation according to high school GPA and SAT scores as well as declared major. The composition of the class for our study included students with majors in biology, chemistry, forensic science and law, and physical therapy. The GPA of students in the class ranged from 2.93 to 4.9 (above 4.0 due to weighted International Baccalaureate and Advanced Placement Courses) with a mean GPA of 3.86. The class consisted of 42 students who were assigned (via the regular registration process) into two laboratory sections. The morning section consisted of ten female and 12 male students (all Caucasian), and the afternoon section contained 13 female and seven male students (Caucasian except for one African-American). The university's Institutional Review Board committee had reviewed and approved the research and advised on the protection of participants. For example, only the research director had access to the data; and this data was only shared in final form with the second and third authors. An ID system was used during data collection so that the research director did not know the names of the students. A protection of human subjects below 18 years of age resulted in the reduction of the number of participants who contributed data for analysis to 39, with 19 students in the HOL-first and 20 students in the VRL-first condition.

The Research Protocol

First the students completed tests of gel electrophoresis concepts and experimental design. Next, the second author introduced the scientific applications of DNA fingerprinting; and the first author explained the experimental protocol and the problem solving scenario. Afterwards groups of students experimented with either the virtual laboratory or the hands-on apparatus. These steps were followed by students using the environment (HOL or VRL) they had not previously used. After inquiry, students individually completed the post-test, answering the same questions they did at the onset of the study. As the final step students filled out a reflective questionnaire about their learning experiences. The protocol spanned three, 150-min-long classroom sessions. For this article we focused on the analysis of students' pre- and post-tests and their reflective questionnaires using the measures explained below.

Instruments and Measures

The pre- and post-tests yielded quantitative data on students' experimental design and conceptual knowledge, and the reflective questionnaire yielded qualitative data about their learning and opinions of the benefit of each environment. The *end-state knowledge* measure

documented students' knowledge before and after inquiry as related to the concepts of (a) the charge of the DNA molecule, (b) the characteristics of agarose gels as related to DNA fragment-separation, (c) the mechanisms by which voltage and concentration affects the travel of DNA fragments, (d) the logical setup of gel electrophoresis, and (e) the practical application of results. In addition, this measure included students' ability to (f) perform correct experiments by using and evaluating scientifically appropriate, experimental controls. Students could receive the maximum of 35 points on their pre- and post-tests. In addition, *qualitative data* was collected from students' self-reports of learning and their opinions on working with the two environments. The reliability of data coding was established by two independent evaluators. After evaluating a subset of the tests individually, the two coders reached an agreement on an effective coding scheme and completed all remaining coding using this methodology.

Data Analysis

For the quantitative analysis we used an ANCOVA model so as to control for any possible differences in the two groups as a result of the quasi-experimental design. This method removes selection bias that can weaken internal validity. The software tool SPSS v.16 was employed using the alpha level.05 to establish significance. Qualitative data from students' reflections on learning were categorized to corroborate the quantitative findings and to help us further refine the instructional approach. The results are summarized below.

Results

Which Order-Condition is More Beneficial for Students' Knowledge Development During Inquiry Learning When Possible Differences in Prior Knowledge are Controlled?

To measure the effect of order condition on students' learning via inquiry, an ANCOVA model was used with students' prior knowledge (from their pre-tests) as a covariate. With this method, we focused on whether there was any effect of using the VRL first or the HOL first, after possible, initial differences in students' knowledge had been equalized. The results indicated that the effect of order on students' end-state knowledge (after inquiry) was not significant [F (1, 36)=1.67, p=0.21, eta squared=0.04]; however, starting with the VRL-based inquiry did yield an increase of 1.26 points on average when two students with equal prior knowledge scores were considered. This result confirmed our hypothesis but also drew our attention to the slight benefit of starting the instructional sequence with the VRL inquiry. While the ANCOVA analysis also indicated the students' significant learning after inquiry [F (1, 36)=12.78, p=0.001, eta-squared=0.253], we focused our analysis on the possible differences in students' experiences in the two environments. Thus, the next analysis considered students' opinions as expressed in their reflective questionnaires.

What are Students' Self-Reported Experiences About the Benefits and Disadvantages of Working with the Two Learning Environments?

Students' reflections clearly indicated that they recognized the benefits of using a VRL due to the (a) added illustration of the mechanisms of the movement of different-size (small, medium, and large) DNA fragments, (b) the ease and speed of experimental design, and (c) the process of automation which helped them synthesizes their knowledge without the error

common in the HOL environment. Students also noted the benefits of the real-life HOL environment which helped them learn (a) the manual skill of loading DNA without puncturing the gels, (b) the effects of their erroneous reversal of the positive and negative poles, and (c) the effects a variety of measurement and design errors that can contribute to the interpretation of results.

It was interesting to see that 84% of the 19 responses we received from the VRL-first group suggested that this sequence (VRL-First and HOL-second) was very helpful. On the other hand, 72% of the 18 responses we received from the VRL-second condition indicated that the VRL did not provide valuable addition to students' experience after the HOL. This is an important result that suggests a different pedagogical approach for order condition than the one suggested by the quantitative data. To explain these opinions, students noted some of the problems they experienced while moving between the two environments. For example, they recognized the presence of error in the HOL which was missing or simplified in the VRL environment. This difference made their experience both challenging and informative. Furthermore, they also noted a problem caused by the attempt of VRL designers to simplify students' initial experiences by automating the ending process of gel electrophoresis—provided students did not stop the experiment manually. This software-design decision resulted in a slightly different effect of voltage as compared to the HOL. This created a cognitive conflict. While students in our study resolved this cognitive conflict with reflection and discussion, this result is important for the further instructional design considerations of practitioners.

Discussion

For effective instructional design, practitioners have to coordinate the goals of instruction, the activities by which these goals are achieved, and the methods of assessment. However, this coordination is alive with challenges. We have illustrated some of these instructional design challenges in this article. The goal of instruction in this unit was for students to be able to understand and apply gel electrophoresis concepts, specifically the effects of concentration and voltage. The learning activity by which the instructional goal was to be achieved included the use of two different environments for inquiry learning: a virtual laboratory and hands-on inquiry. The integration of these two environments achieved its goal and our research results indicated that each of the environments provided a characteristic support for students' learning while extending their inquiry skills.

Was there an effect of order condition? In answer to the first research question, we found that the different order-conditions did not result in significantly different end-state knowledge. The post-instruction tests indicated that the score of students in the VRL-first condition was slightly (by 1.26 points on average) higher; however, this difference was not significant at the alpha level 0.5. That is, the quantitative analysis suggests to practitioners, as well as curriculum designers, that they may decide to choose any specific order of presentation without significant difference in effect on student-learning. However, the examination of students' reflections provided further detail on students' experiences with the two environments.

Students' Self-Reported Experience During Inquiry While the quantitative data indicated that working with the two environments significantly improved students' knowledge, the combined experience also posed significant challenges, which students had to overcome via reflection and discussion. Because students' tasks were slightly different within the two environments, they reported that the different order-conditions did lead to slightly different

experiences. Whereas students' indicated their manual difficulties with the HOL, they also noted several benefits made possible by this environment, which were crucial for their learning. For example, the HOL resulted in students' recognition of the role of error in real-world situations, which had been purposefully omitted in the VRL. Furthermore, the additional visual support provided by the virtual laboratory software was noted as beneficial by students. However, several students experienced difficulties due to the attempt of the VRL to alleviate possible student errors by the automatic stop of the process. This resulted in slightly different voltage effects between the HOL and VRL environments. Whereas cognitive conflict can be beneficial for learning, specifically when one needs to change prior misconceptions, it is clear from these results that we will have to modify our instructional approach by increasing support of students' discussion so as to increase their learning. The pedagogy refined based on these research results will prompt students to stop the process before the automatic ending to reduce this added cognitive load.

The research results indicated that students responded most positively to the order of VRL-first, HOL-second; however, we do not have a detailed understanding of students' experiences during inquiry—only their post-inquiry reflections on learning. Consequently, our future research design should focus on detailing students' experience *during* their inquiry processes and specifically their conceptualization of error in the two different environments.

Educational Significance and Continued Research

The educational significance of the study is that it provides a practical model for the integration of virtual laboratories with hands-on inquiry in higher education classrooms. Using the popular domain of DNA science, our study measured students' learning as well as their challenges using the two different environments. Based on the results, the extension of the study is under development with focus on the processes of knowledge construction during inquiry. The essence of the approach remains to provide a real-life inquiry experience for students so as to generate their interest and fuel their motivation for continued learning. We now have exploratory data to improve our approach, and thus we offer these initial findings to our colleagues for refinements and integration in their own classrooms. We trust that this account of our research will assist colleagues in their development of pedagogical expertise about establishing an inquiry learning environment as much as it helped us refine our own understanding of incorporating real-world experiences to higher education classrooms.

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