Comparative Study of Hands-on and Remote Physics Labs for First Year University Level Physics Students

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Abstract:

With the present zeitgeist, science educators worldwide are developing robotically controlled lab equipment for students to use to perform science experiments remotely. Such use of shared resources, if pedagogically justified, has several advantages: there are cost savings (needing only one lab setup instead of a class set and reduced setup/takedown time); marginalized students, students in remote communities, and disabled students and students with care giving responsibilities can access labs; labs can offer flexibility in the timeframe in which the experiments can be conducted; experiments can be done collaboratively with others at remote locations; experiments can be re-run and refined by students; and a larger variety of experiments can be offered (including ones normally too expensive or dangerous). A pilot study was done comparing the performance of two groups of students conducting a typical first year university level physics lab using a traditional face-to-face lab format and the remote web-based science lab technology. No significant differences in the work the students produced were found. Student experiences with respect to a set of learning objectives derived from a meta-analysis of the literature were also investigated and no significant differences were found. One of the strengths of this study is that it uses a comprehensive set of science lab learning objectives, as opposed to previous research, which tends to focus on learning objectives relevant specifically to the technology being evaluated. A study is planned for a larger group of students so that results may be generalized for all post- secondary science students.

Key Words:

remote laboratory, distributed learning, shared resources, elearning, online science laboratory, remote web-based science laboratory, robotic laboratory.

Introduction

In science education, supported by theories of instruction including inquiry learning, anchored instruction, and constructivism (Corter, Nickerson, Esche, Chassapis, Im, & Ma, 2007, p. 2), there is a widely-held belief in the value of experimentation and laboratory work. In recent years, a zeitgeist has occurred with the independent worldwide development of remote web-based science lab technology. Students may now log onto the web site of a remotely located science lab and request control of remote instruments, including instrument and camera controls, through an interface. Data is then collected in real time and real experimental work is conducted at a distance. Although scientists have, for years, been using remotely controlled instrumentation such as telescopes, deep sea submersibles, Mars Exploration Rovers, as well as conducting collaborative project work on remotely located sub-atomic particle accelerators such as TRIUMF, the application of this technology to education is new. Whether remote lab technology can provide students with learning experiences that meet the learning objectives of traditional lab science is controversial, and there is very little in the research to settle the debate. This research study provides a model that can be used to evaluate the technology and learn about the ways it is effective.

If remote web-based labs can be shown to an effective tool for the types of things we want students to learn from lab science, they have many advantages over the traditional science lab format: cost savings (they need only one lab setup, instead of a class set and reduced setup/takedown technician time); access to labs by more students worldwide including students in remote communities, disabled students and students with care giving responsibilities that are marginalized from regular science work (Scanlon et al., 2004); and remote web-based experiments can be re-run and refined by students. In one study, students reported that “the ability to repeat labs is valued greatly” (Sicker et al., 2005, p. 12). Remote web-based labs may offer flexibility in the timeframe in which the labs can be conducted. In observations of the PEARL project (Cooper, 2005, p. 2), it was found that the remote web-based labs were frequently accessed during the night hours, and the students preferred this flexibility. Further, a larger variety of lab experiments (including ones normally too expensive or dangerous) can be offered remotely. This is another advantage over traditional labs. For example, experiments in radioactivity or conservation of momentum involving the use of a gun to shoot a bullet into a block of wood would not be practical in a traditional lab, but could be safely explored remotely. In addition to these advantages of remote web-based science labs, they also allow for a new type of homework: “A reasonable use of sensibly chosen real experiments as remote labs allows a new form of homework and exercises, as well as project work” (Grober et al, 2007, p. 127).

Proponents of remote web-based labs also point out that as time goes on, the line blurs between real and remote lab experiences. More and more instruments are controlled by mouse and keyboard, as the computer replaces instruments such as the oscilloscope, making the operation of equipment remotely or in person more the same than different (Nickerson et al., 2007). An extension of this is the so-called *collaboratory*. Multi-university experiments are becoming more common because of the affordance of remote data collection that networked computers provide, and exposing students to this experience may be of value. Indeed, the trend towards sharing sophisticated instruments on the Internet is growing:

The Grid2003 Project has deployed a multi-virtual organization, application-driven grid laboratory (Grid3) that has sustained for several months the production-level services required by physics experiments of the Large Hadron Collider at CERN (ATLAS and CMS), the Sloan Digital Sky Survey project, the gravitational wave search experiment LIGO, the BTeV experiment at Fermilab, as well as applications in molecular structure analysis and genome analysis. (Foster, Kesselman, & Tuecke, 2001, p. 1)

Universities of the future will have the ability to network experiments for their students in a similar way (Wulf, 2003). The possibility of setting up remotely accessible science lab experiments in many different universities that allow students to share access to them all has some unique advantages:

A worldwide network of clusters of remote labs should be the long-term outcome, offering various experiments. The advantages are obvious: the maintenance of real experiments is not borne by just one institution; everyone can learn from each others' experiences; synergies can be used to solve technical problems; different cultural approaches to install, implement and test a remote lab in learning environments will evolve. (Grober et al., 2007, p. 139)

This shared infrastructure has pedagogical implications. For students who pursue careers in science after graduating, the experience of working in the realistic collaboration with others using shared resources may well be valuable experience. Certainly, the advantages of collaboration in learning has been well established (Pea, 1993).

In the past fifteen years or so, various remote web-based science lab activities (or labs) for students learning science have been developed and documented in science, engineering and education journals. This literature tends to describe these labs and provide rationale for them (Alhalabi, Marcovitz, Hamza, & Hsu, 2000; Aliane, 2006; Bohne, Faltin, & Wagner, 2002; Cooper, 2005; del Alamo et al., 2002; Ertrugrul, 2000; Esche, 2005; Feisel & Rosa, 2005; Forinash & Wisman, 2005; Grober, Vetter, Eckert, & Jodl, 2007; Harms, 2000; Hesselink et al., 2000; Nedic, Machotka, & Nafalski, 2003; Nickerson, Corter, Esche, & Chassapis, 2007; Ogot, Elliott, & Glumac, 2003; Schauer, Ozvoldova, & Lustig, 2008; Sicker, Lookabough, Santos, & Barnes, 2005). Remote web-based science labs typically originate in the area of engineering at larger universities like MIT and Stanford and are often named with an acronym or some other name to identify the lab with the developers. One of the earliest is CyberLab at Stanford (Hesselink et al., 2002). One of the largest is the PEARL project (http://iet.open.ac.uk/PEARL), a major European Union funded project that concluded in 2003 (Cooper, 2005). While these labs vary in many respects, there has been a convergence in the technology used for development and implementation with National Instruments' LabView being the most successful software platform for the computer interface. Appendix A shows a cross section of the remote web-based science labs that have been developed worldwide and the literature describing them.

In a worldwide inventory taken in 2006, Grober et al. (2007) found that in "about one-third of remote labs dealing with physics and about two-third dealing with engineering techniques […]. Only a few remote experiments were related to other disciplines like chemistry, for example" (p. 129). Recently, a much more versatile remote web-based lab suitable for all science subjects has been developed by North Island College (NIC) (see http://rwsl.nic.bc.ca/about.html). Since remote web-based science labs are relatively new, many current projects are not yet documented in the literature. Based on the amount of attention paid to the development of remote web-based science labs in recent conferences, we can expect advances in this area to soon appear in the literature, in particular with applications to biology and chemistry in addition to physics and engineering.

Problem Statement

At present, there is widespread development of remote web-based science labs and extensive literature documenting what is being done and providing rationale for it. This development is expensive and is often funded by public funds such as BCcampus and NSF. While there is ongoing debate about the merits of remote web-based science labs in comparison to the other possible types of labs and, at the same time, so much development of them, there is disproportionately little research evaluating their effectiveness. In order to make good pedagogical decisions about the implementation of remote web-based science labs, it is crucial to evaluate their effectiveness. It is also important to learn how students experience them to inform their design and application to optimize their educational value.

Research Purpose and Questions

Research Purpose

The purpose of this research is to compare the performance of two groups of students conducting a typical first year university level physics lab using a traditional face-to-face (F2F) lab format and a remote web-based science lab format to see if there are any differences in effectiveness of the lab formats. The research will also investigate the experiences of the students with respect to science learning objectives to see in what ways, if any, the two formats differ.

Research Questions

This research consists of a controlled experiment with mixed methods data collection to answer the following questions:

How do first year university level physics students' lab *performance* compare when completing a typical first year university level physics lab in a traditional F2F lab format to completing the same lab in a remote web-based format?

2) How do first year university level physics students' *experiences* with respect to science lab learning objectives compare when completing a typical first year university level physics lab in a traditional F2F lab format to completing the same lab in a remote web-based format?

Research Approach and Rationale

The research consists of a controlled experiment with mixed methods data collection to compare the performance and experiences of twelve first year university level physics students completing a typical first year university level electricity and magnetism lab in a traditional F2F lab format to those completing the same lab in a remote web-based format. The research presented here is primarily concerned with the evaluation of remote web-based science labs as compared to the traditional F2F lab format. There are two general ways that student learning as a result of their lab work is evaluated: 1) student *performance* as measured by the grades on their lab reports determined using the standard grading rubric used to evaluate student lab work, and 2) the student *experiences* with respect to science lab learning objectives determined by answers to questions on a questionnaire completed by the students after the lab is completed.

The Experiment

An experiment was chosen to allow for a causal relationship to be established, if one exists, between the format used to conduct a lab and the student performance and experiences that result. Participants were randomly assigned to two groups: one group conducted the lab using the remote web-based technology and the other group conducted the lab in the traditional F2F lab format.

Lab *performance* as measured by the grades on the resulting lab reports of the two groups of students generated quantitative results used to compare performance of students using the remote web-based labs to those conducting traditional F2F labs.

Student *experiences* were also investigated in terms of a particular set of learning objectives. In reality, learning objectives for science labs vary by subject area among other things. For engineering, the educational goals proposed by the Accreditation Board for Engineering and Technology (ABET, 2005) are the most widely accepted. For physics, the American Association of Physics Teachers' "Goals of the Introductory Physics Laboratory" (AAPT, 1998) are often referred to as well as others. Problematically, when remote web-based science lab evaluation has been done in the past, it's been done with reference to different sets of educational objectives. It is at least partly because of this that there is no consensus in the evaluation of various remote web-based science labs. The debate about the different modes of delivery of science labs is "confounded by the use of different educational objectives as criteria for judging the laboratories" (Ma and Nickerson, 2006, p. 1).

Ma and Nickerson (2006) conducted an extensive literature review comparing traditional F2F labs, virtual labs and remote web-based labs. It was found that by selecting, coding and categorizing 60 of the most relevant articles from 1000 articles found on the subject (which were dispersed over 100 different journals and conferences), that there was no standard common criteria used to evaluate the effectiveness of lab work. The articles measure against different objectives, and therefore all seem to be able to claim superiority (p. 7). A four-dimensional model was built by Ma and Nickerson (see Table I) based on the educational goals proposed by the Accreditation Board for Engineering and Technology (ABET, 2005) and other available taxonomies of lab work by which the articles could be compared (Ma & Nickerson, 2006, p.8).

Table I Learning Objectives of Science Labs

Lab Objectives	Description	Goals from ABET
Conceptual Understanding	Extent to which laboratory activities help students understand and solve problems related to key concepts taught in the classroom.	Illustrate concepts and principles
Design skills	Extent to which laboratory activities increases student's ability to solve open-ended problems through the design and construction of new artifacts or processes.	Ability to design and investigate Understand the nature of science (scientific mind)
Social skills	Extent to which students learn how to productively perform engineering-related activities in groups	Social skills and other productive team behaviors (communication, team interaction and problem solving, leadership)
Professional skills	Extent to which students become familiar with the technical skills they will be expected to have when practicing in the profession	Technical/procedural skills Introduce students to the world of scientists and engineers in practice Application of knowledge to practice

This model was used in the research to design the questionnaire completed by all of the participants after they performed the lab (see Appendix B). A questionnaire was used so that student experiences with respect to learning objectives could be isolated from each other and any resulting differences could be related to individual objectives. The questions were chosen to address the entire range of learning objectives in this model in an attempt to reveal any important differences between the traditional F2F and remote web-based labs with respect to these objectives. Closed ended questions were chosen to focus on elements of the learning objectives. This was preferable because the scope and depth of responses could be predicted based on the existing features of the lab topic and the nature of the objectives. Closed ended questions also limited the time required by the students to complete the questionnaire, which was important for obtaining maximum participation as well as being sensitive to the students' time constraints. Since the aspects of lab work that the questions focus on are not naturally ordered, questions with nominal scales were used. The answers resulted in qualitative data appropriate for a comparison of the experiences of the participants with respect to the learning objectives as a result of the different lab formats.

The Lab Topic

The e/m (ratio of the charge of an electron to its mass) lab topic was chosen for a variety of reasons. This is a typical fundamental lab that is seen in most first year university level physics courses, so the lab topic is relevant to a very wide audience. The topic of the lab is controlled for between the traditional F2F and remote web-based lab formats since the same lab is possible for both groups. The e/m lab investigates a fundamental topic in physics, relating electric current in coils of wire (Helmholtz coils) to the voltage applied to electrons (traveling perpendicular to the magnetic field produced by the current in the Helmholtz coils) and the radius of curvature of the resulting path of the electrons. The path of the electrons is a visible beam of blue light that can be seen as a straight line or bent into a circular path produced by the ionization of helium gas in a closed bulb. The apparatus allows for a striking visual representation of the relationship between current, voltage and radius of the beam, which is difficult to visualize otherwise. The students make both qualitative observations and quantitative measurements when conducting the lab. The e/m lab involves the entire range of learning objectives outlined in Ma and Nickerson's model: conceptual understanding, design skills, professional skills and social skills (2006, p. 8), and therefore the choice of this particular lab allowed the widest possible range of data to be collected. See Appendix C for the description of the e/m lab used by the participants.

Rationale

An experiment with both quantitative and qualitative data was chosen for several reasons. The experiment generated quantitative results based on student *performance* as determined by lab grades that provides evidence regarding how remote web-based labs compare to the traditional hands-on lab format in terms of that outcome measure. Since the research also investigated the *experiences* of the students with respect to lab science learning objectives, qualitative data was collected to allow results to be described thematically.

Methods - Detailed Procedures

Participants and Context

The participants for this study were students registered in a first year university level physics class at a BC university in the summer semester of 2010. The students were registered in a single course attended in person for two-hour classes, twice per week. The class limit for the course is 35 students. The physics course content focuses on optics, electricity and magnetism. Students are also required to register for a three-hour lab, once per week. The students are required to register in one of two separate lab sections (since there is a size limitation of 20 students for labs). In the lab, course material is reinforced. Additional areas of learning include measurement, estimation of uncertainty, making decisions about experimental design, measurement, troubleshooting, graphing, analysis of experimental data, drawing conclusions from the results and writing a lab report to communicate what has been learned. There are generally ten such weekly labs per course, and they take approximately one to two hours to perform and two to three hours to complete including a lab report. The lab has a lab instructor who is not the course instructor. The lab instructor is responsible for assisting the student with lab work and grading the lab portion of the course which typically counts for 25% of the total course grade. The technician of the host institution of the remote lab is one of the developers of a robotically controlled lab apparatus and interface. He set up the lab equipment and worked with the researcher to facilitate student access to the remote apparatus.

Sampling

The participants for the experiment were selected on a voluntary basis from the class. The researcher approached the class at the beginning of the semester and explained the study and handed out a consent form to the class clearly explaining that participation is voluntary and that not participating would not affect their treatment by the lab or class instructors in any way. The researcher randomly assigned the participants into two groups, regardless of which lab section they were registered in so that any effect due to the students' lab section would not affect the outcome of the experiment. One of these groups was randomly assigned to be the control group and no intervention was given to this group (i.e., they completed the lab as they normally would). The other group was assigned to be the experimental group, and this group completed the lab via the remote web-based science lab at NIC during the same week that the control group completed the lab.

The Lab Activity

The lab conducted by the participants was a typical electricity and magnetism experiment in which the objective is to determine the charge to mass ratio of an electron. The lab is described in the lab manual purchased for the course, and this description was used by both groups (see Appendix C). The questionnaire completed by all of the participants was an electronic questionnaire accessed from a link on the course web page. The control group attended the lab in the regular timeslot for that lab. The students were given the option to work alone or in pairs as is always an option for students, given space in the lab.

The experimental group was directed by the class instructor to their course web page, which included a link to a schedule in which the students could choose a lab time to complete the lab and a link to the remote web-based lab. The researcher set up the schedule by determining the times when the remote lab could be accessed during the same week that the control group completed the lab. There were certain considerations beyond the researcher's control, such as when a technician was available at the remote site in case problems were encountered. The participants in the experimental group had the option to sign up to work alone or in pairs. The option to work alone or in pairs was therefore the same as it was for the control group. Participants in the experimental group were instructed to come to a room at the university in which a computer had been set up for the remote web-based lab. It should be noted that the operation of the remote web-based lab may be accessed from any computer having a standard web browser, but due to some software issues that still exist in the remote web-based lab technology at NIC, it was necessary for the students to come to a computer set up by the researcher for this purpose.

The experimental group's participants logged in to the NIC remote web-based physics lab at the scheduled time and proceeded with the lab. There were some additional controls that are not part of the traditional lab including a camera selection radio button, but their operation was clearly indicated on the interface, and the students had no problems navigating these features. All other controls were the same as the lab interface seen in the traditional F2F lab since the same model of the apparatus, the Nakamura (B10-7350) e/m apparatus, was used in both cases and the interface allowed control of the same parameters by mouse. The researcher was present in case students had problems with the remote web-based lab, to simply aid in issues relating to the technology. In two cases, the remote lab server had to be reset, and the researcher was required to phone the remote lab to reset the server. Measurements were not lost in this process, and the students continued where they had left off.

Performance Measure

The independent or treatment variable for the experiment was the lab format that students used for completing the lab. The dependent or outcome variable was the student lab performance as measured by grades on the lab reports determined in the usual way lab reports are graded for this course. The students collected data for the lab and wrote a lab report according to lab report format criteria given at the beginning of the semester. This requires the use of a lab notebook for pre-lab work and for recording raw data in ink, the use of Excel to perform calculations including uncertainty calculations and graphs, and the use of a word processor to write up the lab report.

The lab instructor graded the lab reports according to the standard rubric used for all levels of physics labs at this university. In addition to the assessment of the lab performance by the lab instructor, the researcher, who is also frequently a lab instructor for this course, graded all of the lab reports to increase reliability of the results. For the purposes of assessment, the lab instructor and the researcher were blinded to the group assignment of the students by a process of coding the lab reports. This blinding was possible because the lab was chosen so that lab objective, theory, apparatus, data, results and analysis were identical for both the control and experimental groups and there was no way to distinguish between the lab reports done by the two groups.

The Questionnaire

The research included qualitative measures as well as the quantitative performance measure described above. All participants including the participants in the control and the experimental groups were required to complete a questionnaire based on their experiences with respect to questions based on the four-dimensional model proposed by Ma & Nickerson (2006) for lab objectives of science lab work (see Appendix B). The twelve questions on the student questionnaire were designed around these four broad categories: conceptual understanding, design skills, social skills and professional skills, with three questions per category. The questions on the questionnaire took the participants approximately ten minutes to complete. The questionnaire was completed after the participants completed the lab and before the graded labs were returned so that the time participants responded was as soon as possible after completing the lab and so that lab grades did not influence student answers.

It should be noted that many of these questions were included because they are based on the learning objectives in the Ma and Nickerson model (2006) discussed earlier, and although this particular lab was chosen to be a good candidate for most of the lab objectives, it did not lend itself equally well to all of the objectives. This experiment, including the choice of questions, is designed so that it could be used with any lab topic, and therefore a broad representative selection of questions is represented in the questionnaire. In this way, general learning objectives could be investigated over a series of labs in the future (and not restricted to one lab as in this study) to gain a more realistic representation of what students experience in terms of lab objectives in the full lab component of a semester long course, for example. This explains why some of the questions may appear to be less relevant than others in this study.

Results and Discussion

5.1 Lab Performance

Descriptive statistics for the grades on lab reports for the control group and the experimental group are shown in Table III, separately by condition. The control condition is the traditional F2F lab format, and the experimental condition is the remote web-based lab format. The lab grades were calculated as the average between the lab instructor's grade and the researcher's grade. The sample size for the experiment was 12 participants in total.

Table III. Lab Grades (reported as mark out of 10) on the Student Lab Reports, by Condition

	Mean	Std. Dev.	N
Control Condition: F2F Format	8.3	1.2	6
Experimental Condition: Remote Lab Format	8.0	0.3	6

Although a t-test comparison would be preferential for generalizing the results to a wider population, the small sample size in this study (N=12) made it more appropriate to do a simple comparison of the means of the grades and their standard deviations. According to the grades on the lab reports, the means for the control and experimental groups were 8.3 with a standard deviation of 1.2 and 8.0 with a standard deviation of 0.3, respectively. The means are contained within the ranges of each other, and, therefore, there is no significant difference between the mean scores. That is, there is less than 5% chance that there is a difference between the control and experimental groups in the larger population or a 5% chance of a type II error (a false negative).

Similar studies comparing effectiveness of remote web-based lab format compared to traditional hands-on lab format (Nickerson et al, 2007; Corter et al, 2007; Ogot et al., 2003; Sonnenwald et al., 2003; Scanlon et al., 2004; Sicker et al., 2005) show similar results. It could be that the performance in remote web-based labs is indeed at least equal to that of traditional F2F labs as these previous studies suggest and that this study confirms these findings.

Studies with larger sample sizes and more lab topics over more science subjects would be beneficial in establishing if this conclusion is true of the larger population of all post-secondary science students. If it is, then there may be evidence to justify the development of remote web-based lab technology to be used in distributed learning of science to enable students to study science including the lab, while meeting the desired learning goals that this entails. The benefits of this include being able to provide science education at a lower cost since the lab equipment needed for a remote lab is a fraction of what is needed in fully equipped traditional lab. In addition to this, it would enable students who are marginalized from the traditional modes of learning science due to disabilities, care giving responsibilities, and remote locations an opportunity to study science as has been the prerogative of students attending a traditional post-secondary institution. And there are many other advantages as described in the introduction of this paper.

5.2 Students' Experiences with respect to Conceptual Understanding Learning Objectives

No apparent differences appeared between groups' experiences with respect to the questions on the conceptual understanding learning objectives; thus, it may be that remote web-based labs offer an equivalent lab experience to traditional F2F labs. More studies with larger sample sizes and perhaps tests measuring mastery of material as opposed to subjective self-reported experiences would be useful in establishing the effectiveness of remote web-based technology with respect to conceptual understanding.

5.3 Students' Experiences with respect to Design Skills Learning Objectives

Neither group responded positively that they had experiences reflecting the design skills learning objectives as expressed in Nickerson and Ma's model. This could be due to the nature of the lab itself. Lab design must include opportunities for these experiences to happen. Repeating this study with a variety of labs may reveal more experiences with this lab objective, or it may reveal that this lab objective is rarely met in lab science regardless of the lab topic. More research will need to be done to investigate this issue.

5.4 Students' Experiences with Respect to Professional Skills Learning Objectives

Table IV summarizes the responses by the participants when asked to "Please list the skills you became more familiar with. Note: you can select as many as you like (or none)." This table shows which skills individual participants chose which enables individual differences or patterns to be seen. The participants in the control group chose an average of 2 skills each, while the experimental group chose an average of 3.3 skills each. This difference may be important and may imply that the remote lab group felt that they had experienced more learning about professional skills than their control group counterparts. Further studies are needed.

Table IV Lab Skills Students Identified as Having Learned More about as a Result of Performing the Lab

	Control Group: F2F Format						**Experimental Group: Remote Lab Format**					
Participants	1	2	3	4	5	6	1	2	3	4	5	6
Uncertainty estimation/propagation	**X**	**X**				**X**			**X**			
Measurement	**X**				**X**	**X**		**X**		**X**	**X**	
Control of physical controls on the apparatus		**X**	**X**		**X**		**X**	**X**		**X**		**X**
Use of internet for measurement							**X**	**X**	**X**	**X**	**X**	**X**
Use of internet for other							**X**				**X**	**X**
Calculations									**X**			
Graphing												
Analysis	**X**				**X**	**X**					**X**	
Communication (report writing)		**X**							**X**			
Communication of results (oral)												

Conclusions

Limitations and Strengths

There are some limitations to the design of this research study including the small sample size and the fact that all students did not experience both lab formats (ideally, with order reversed for half of the participants) so that a paired t-test could be done. The participants came from two lab sections (of the same physics course), and the lab instructor was different for each lab section. Lab instructor should be controlled in the future by choosing sections of labs with the same lab instructor. Also, descriptive statistics of the participants were not taken on the sample to allow comparison to the characteristics of the target population, and this limits the ability to make inferences from the sample to the target population of all post-secondary lab science students.

On the other hand, the sample was chosen from the entire population of students for a standard first year physics course at an accredited Canadian university, and variables between the control and experimental groups such as lab topic, lab procedure and equipment and the course instructor were controlled. There are several other strengths in this study design in comparison to previous research on this topic. For example, this study was designed around a lab activity that has a high level of interactivity; media richness, real time data collection and an identical lab activity was used for both the control and experimental groups. Also, the questionnaire used was designed to investigate learning objectives as identified by a meta-analysis of lab objectives for a wide range of post-secondary science courses cited in the literature (Ma & Nickerson, 2006). Since previous research on this topic lacks these particular strengths, the results from this study provide a good starting point for a series of future studies that have the strengths of this design but do not have the limitations mentioned above. This study design would be easily replicated with other sample populations within the target population and easily scalable to larger sized sample sizes, which would strengthen the ability to make inferences to the target population.

Future Direction

In this research study, students conducting a physics lab using remote web-based technology and students using the traditional F2F format were compared, and no differences in effectiveness were found. There were some differences in the experiences of the participants with respect to certain lab learning objectives, but there was no indication that one format was superior in general. This research study, although done with an insufficient sample size to generalize to the population of all post-secondary lab science students, provides a model that can be used for further studies in this area. If the results from other studies are found to be consistent with this one, they may provide evidence that remote web-based lab technology has the potential to be a useful tool for science educators. This study also points to some of the areas that are of interest to explore, such as the inclusion of opportunities to design solutions for solving problems, the number and variety of professional skills practiced and the role of social interactions, including lab instructor presence. This, in turn, may inform the development of the technology (and labs themselves).

The advantages of remote web-based labs make this prospect worth exploring. The few studies that have been done, including this one, are promising. More research is needed to learn in which ways various formats for science labs are beneficial to student learning. Since there are other formats not looked at in this study, such as virtual labs involving simulations or learning objects, it would also be useful to study these formats to learn about their effectiveness. What is the relative effectiveness of simulation versus remote access of real equipment? Can users even tell them apart?

There is disagreement over whether or not a simulated laboratory can be as effective in meeting objectives as remote access to an experiment consisting of physical equipment. This can be explored experimentally by having students evaluate the two kinds of experiences. It would be valuable to see if a student working over the Internet can tell the difference between a physical and a simulated experiment. Students could be asked to complete the online experiment and then indicate whether they thought they were dealing with real equipment or a simulation. It will be necessary to have user interfaces that appear to be operating real equipment but are really providing access to simulations. (Feisel & Rosa, 2005, p. 122).

If there are specific ways that learning lab science can be better facilitated by one format over another, it may even be useful to blend the different formats to optimize student learning. Nickerson (2007) has suggested that a *theory of appropriateness* be developed as a way to know when and under what circumstances remote web-based science labs, for example, should be chosen as a format for students' lab work:

Generally, it may be possible to build a theory of appropriateness, in which for certain educational objectives certain technologies, with associated coordination processes, achieve educational goals more effectively. Right now, the evidence on which such a theory should be based is still scant, and without further research educators risk at the one extreme ignoring technologies which are cheaper and equally effective, and at the other extreme, dropping current labs in favor of less expensive but less effective technology. (Nickerson et al., 2007, p. 722)

These research ideas can be broadened to answer many other questions. Does the effectiveness of remote web-based labs depend on lab topics or subject areas (e.g., biology and chemistry)? Do student characteristics matter with respect to the lab format that is most effective (e.g., introverted learners, visual learners and more flexible learners)? Are there benefits to students who do collaborative lab work with students at different locations using remote web-based science lab technology? Does the access to more sophisticated instruments benefit learners? Do cultural differences matter for the effectiveness of remote web-based lab technology? What are student preferences with respect to the lab format (e.g., convenience, ease of setup and use, reliability, time commitment)? What are instructor and technician preferences? What features/affordances of remote web-based lab technology are important for meeting desired learning outcomes (e.g., real-time, fidelity, interactivity)? Are there any features that can be incorporated into remote web-based labs to increase their effectiveness beyond the traditional F2F format (e.g., high speed cameras or tools for collaboration)?

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Appendix A

A cross section of remote web-based science lab projects worldwide

Name	University/Learning Institution	Country	Reference/Literature
PEARL	Open University, University of Dundee, Trinity College, Universidade de Porto, Zenon SA	EU (UK, Scotland, Ireland, Portugal, Greece)	(Cooper, 2003)
WebLab	MIT	USA	(del Alamo, Brooks, McLean, Mishuris, Chang & Hui, 2003)
RCL	Technical University of Kaiserslautern	Germany	(Grober, Vetter, Eckert & Jodl, 2007)
ReLI	University of Colorado	USA	(Sicker, Lookabaugh, Santos & Barnes, 2005)
RL	Florida Atlantic University	USA	(Alhalabi, Marcovitz, Hamza & Petrie, 2002)
MARVEL		EU	(Aliane, Martinez, Fraile, & Ortiz, 2006)
ITLL	Cornell	USA	(Ertrugrul, 1999)
LABNET	Universidad Europa de Madrid	Spain	(Aliane et al., 2006)
TLR	University of Tuebingen	Germany	(Harms, 2000)
I-Lab	Learning Lab of Lower Saxony	Saxony	(Bohne, Faltrin & Wagner, 2002)
SBBT	Oregon State University	USA	(Harms, 2000)
IRLE	Rutgers University	USA	(Ogot, Elliott & Glumac, 2003)
IECATS	Indiana University Southeast	USA	(Forinash & Wisman, 2005)
NetLab	University of South Australia	Australia	(Nedic, Machotka, & Nafalski, 2003)
	Stevens Institute of Technology	USA	(Esche, 2006)
ISES	University of Trnava, University of Zlin and Charles University	Slovak/Czech Republics	(Schauer, Ozvoldova & Lustig, 2008)
CyberLab	Stanford University	USA	(Hesselink, Rizal & Bjornson, 2000)
PCOL	Purdue University	USA	(http://www.chem.purdue.edu/gweaver/projects/pcol.html)
RWSL	North Island College	Canada	(http://rwsl.nic.bc.ca/about.html)

Appendix B

Student Questionnaire

Did you perform the e/m lab in person or remotely?

- In person (in the regular lab setting)
- Remotely (LabView)

Educational Goal Category: Conceptual understanding (Q 1-3)
Extent to which laboratory activities help students understand and solve problems related to key concepts taught in the classroom.

1) In this lab, you saw that the effect of a magnetic field on a beam of electrons. Of the following, which best describes what you experienced?

a I understood that increasing the magnetic field bent the electron beam into a circle for the first time
b The lab confirmed what I expected, that the magnetic field bent the beam into a circle
c The fact that the magnetic field bent the beam into a circle surprised me, and I didn't understand why it happened
d I didn't observe that the increased magnetic field affected the electron beam
e I was confused by what happened to the electron beam when the magnetic field increased

2) In this lab, you saw that by increasing the voltage across the anode and cathode of the electron gun that the radius of the circular electron beam increased. Of the following, which best describes what you experienced?

a I understood that increasing the voltage increased the energy of the electron for the first time

b Seeing the beam radius increase with increased voltage confirmed what I already knew

c The fact that the increased voltage increased the radius of the beam circle surprised me, and I didn't understand why it happened
d I didn't observe that the increased voltage affected the electron beam

e I was confused by what happened to the electron beam when the voltage increased

3) In this lab, you saw that by increasing the current in the Helmholtz coils that the radius of the circular electron beam increased. Of the following, which best describes what you experienced?

a I understood that increasing the current bent the electron beam into a circle for the first time

b The lab confirmed what I expected, that the increased current bent the beam into smaller circle

c The fact that the increased current decreased the radius of the beam circle surprised me, and I didn't understand why it happened
d I didn't observe that the increased current affected the electron beam

e I was confused by what happened to the electron beam when the current increased

Educational Goal Category: Design skills (Q 4-6)
Extent to which laboratory activities increases student's ability to solve open-ended problems through the design and construction of new artifacts or processes

4) There are likely a number of problems you encountered during this lab. Of the following, which best describes what you experienced?

a I was able to create and apply my own solution to at least one problem

b There was only one solution possible and I figured out a way to solve the problems on my own without help from the manual or others

c I re-read the manual to figure out the solution

d I asked the lab instructor or other students for the solution

e I was generally unable to solve my problems

5) With respect to *any* problem you encountered, which of the following best describes your experience?

a I came up with a way to solve it

b I had the opportunity to come up with a way to solve it, but I wasn't able to

c There was no opportunity to figure out a way to solve it

6) With respect to *any* problem that you encountered, which of the following best describes your experience?

a I was able to design and construct something (physical) to solve it

b I had the opportunity to design and construct something (physical) to solve it, but I wasn't' able to

c There was no opportunity for me to design and construct something (physical) to solve it

Educational Goal Category: Professional skills (Q 7-9)
Extent to which students become familiar with the technical skills they will be expected to have when practicing in the profession

7) Please list the skills you became more familiar with. Note: you can select as many as you like (or none).

a Uncertainty estimation/propagation
b Measurement
c Control of physical controls on the apparatus
d Use of internet for measurement
e Use of internet for other
f Calculations
g Graphing
h Analysis
I Communication (report writing)
j Communication of results (oral)

8) Of the skills you chose in Question #7, which did you learn the *most* about relative to what you already knew?

a Uncertainty estimation/propagation
b Measurement
c Control of physical controls on the apparatus
d Use of internet for measurement
e Use of internet for other
f Calculations
g Graphing
h Analysis
I Communication (report writing)
j Communication of results (oral)

9) Of the skills you chose in Question #7, which did you learn the *least* about relative to what you already knew?

a Uncertainty estimation/propagation
b Measurement
c Control of physical controls on the apparatus
d Use of internet for measurement
e Use of internet for other
f Calculations
g Graphing
h Analysis
I Communication (report writing)
j Communication of results (oral)

Educational Goal Category: Social Skills (Q 10-12)
Extent to which students learn how to productively perform engineering-related activities in groups

10) Did you complete any task with another/others during this lab?

a Yes

b No

11) If you worked with another/others, which best describes your experience?

a It allowed us to complete the task easier/better than had I done it alone
b it allowed us to complete the task faster than had I done it alone
c It had no effect of my ability to complete tasks
d It made completing the tasks take longer than had I done it alone
e It made completing the tasks more confusing/difficult than had I done it alone

12) If you worked with another/others, which best describes your experience?

a I took a leadership role
b There was an opportunity for me to lead, but I didn't
c We shared equally in the task
d There was no opportunity for leadership
e I was led by other(s)

Appendix C

Lab Description from Student Lab Manual

Experiment 12

DETERMINATION OF $^{e}/m$

Around the turn of the century, two dramatic experiments established the existence of the electron, a charged particle very much smaller than an atom in size and in mass. In 1897, J. J. Thomson analyzed the motion of cathode rays (electrons) as they passed through electric and magnetic fields. Thomson's investigations gave the following results:

1) The rays consist of particles that have a negative electric charge and a definite mass.
2) The charge-to-mass ratio of the electron was very large, about 2000 times that of a hydrogen ion, the lightest known ion.

From the second result, one can conclude that either the charge on the electron is very much bigger, or its mass very much smaller, than the hydrogen ion. Thomson believed that the latter was the case. Sometime later (around 1909), R.A. Millikan measured the charge on the electron and thereby confirmed Thomson's suspicions.

Objective

To determine the $^{e}/m$ ratio from the graph expressing the relationship between electron accelerating voltage and current in Helmholtz coils for an electron beam with constant radius.

Theory

In this experiment, electrons are "boiled off" a heated cathode inside a specially designed tube (filled with helium at a pressure of about 10^{-2} mm of Hg), and then accelerated by a high potential difference between the cathode and anode. The kinetic energy gained by the electrons as they reach the anode is equal to the work done on them by the electric field, i.e.

(1)

where *m* is the mass of the electron, *v* is the velocity of the electrons, *q* is the charge of an electron and *V* is the voltage between the electrodes that is used to accelerate the electrons.

The electron beam emerges from a small aperture in the anode and enters a homogeneous (uniform) magnetic field produced by a pair of Helmholtz coils (described below). The magnitude of the force *F* that the magnetic field exerts on the electron beam, as the beam enters the magnetic field *B* at an angle is given by

(2)

If the electron beam is directed **perpendicular** to the magnetic field of the coils, then the magnetic force will be perpendicular to the direction of the beam. Thus, the magnetic force changes the beam's direction of motion; it does not change its speed. Furthermore, because the magnetic field is uniform, the magnetic force and, consequently, the beam's acceleration are not only always perpendicular to the direction of motion, but they also have constant magnitudes. These are precisely the characteristics of a particle moving in uniform circular motion. The equation stating that the magnetic force provides the acceleration is given by

(3)

where r is the radius of the circular path of the electron beam.

Combining Equations (1) and (3), we obtain an expression for the electron charge-to-mass ratio $^{e}/m$:

(4)

where the symbol e has been substituted for q.

All but the magnetic field strength B in Equation (4) are directly measurable. B can be resolved into directly measurable quantities by considering the geometric symmetry of the Helmholtz coils. The coils consist of two individual coaxial, circular coils, each of radius R, which have their planes parallel and separated by a distance equal to R. When current is put through the coils, an almost uniform magnetic field is produced over a fairly large region near the centre of the axis of the coils. The calculus solution for the value of the magnetic field at a distance X along the axis of a single loop of radius R carrying a current I is

(5)

where μ_o is the permeability of free space ($\mu_o = 4\pi \times 10^{-7}$ Tm/A).

Since there are *N* current loops in each coil arranged such that their fields add constructively and contribute equally at the centre of the tube, the total coil field is then

(6)

At the centre of the axis of the Helmholtz coils, *X* = *R*/2, and Equation (6) simplifies to

(7)

(We may safely assume that this value of *B*, derived from the central point on the axis of the coils, closely approximates *B* at the position of the electron beam.) Substituting $\square_O$ = 4□□□□10^{-7} Tm/A, *N* =130, and *R* = 0.15 m into Equation (7) gives

$$B = (7.793\times10^{-4}\ \tfrac{T}{A})I \tag{8}$$

where *B* is in tesla (T) when *I* is in Amperes (A).
Substituting Equation (8) into Equation (4), an experimentally measurable value of *e/m* can be obtained from

$$\frac{e}{m} = \frac{2V}{(6.073\times10^{-7}\ \frac{T^2}{A^2})I^2r^2} \tag{9}$$

Since there are three data variables *V*, *I*, and *r*, three different linear plots can be made to verify Equation (9). However, due to the limitations of time and the design of the equipment, you will plot only the relationship between *I* and *V* (i.e., *r* is held constant at some fixed value). Rewriting Equation (9) gives an equation that can be experimentally tested and from which the $^e/_m$ ratio can be determined

$$V = \left(\frac{1}{2}\frac{e}{m}(6.073\times10^{-7}\ \tfrac{T^2}{A^2})r^2\right)I^2 \tag{10}$$

The accepted value of $^e/_m$ is 1.7588×10^{11} C/kg.

Apparatus Nakamura (B10-7350) e/m experimental apparatus
BK Precision Discharge Tube Power Supply – Model 1511 (±1%)
Fluke DMM (± 0.2%)
table lamp

The Nakamura $^e/_m$ experimental apparatus consists of a specially designed tube (filled with helium at a pressure of about 10^{-2} mm of mercury) supported at the centre of a pair of large, parallel-mounted Helmholtz coils (see Figure 1). Within the spherical tube is an electron gun that is composed of a heated cathode (a heated filament is attached to the cathode), a focusing element, and a coaxial anode containing a single hole. The path of the narrow beam produced by the electron gun is visible due to the glow discharge caused by ionizing collisions between electrons and the helium gas inside the tube. To ensure a satisfactory circular beam, the electron path is perpendicular to the axis of the Helmholtz coils. There is a scale inside the tube for measuring the diameter of the path traced by the electron beam.

Connect the jacks of the e/m apparatus that are labelled HEATER to the output voltage 6 (red and blue jacks) of the FILAMENT SUPPLY on the discharge tube power supply. Polarity doesn't matter, as this is an AC voltage. This heats up the filament so that the electrons are, in effect, "boiled off" the anode.

The 0-500Vdc jacks on the discharge tube power supply provide up to 500 V for the accelerating voltage between the cathode and anode. Connect the jacks of the e/m apparatus that are labelled ANODE to the 0-500Vdc jacks on the discharge tube power supply (**red to red** and **black to black**), and make sure the **VOLTAGE MONITOR SELECT switch is set to the left**.

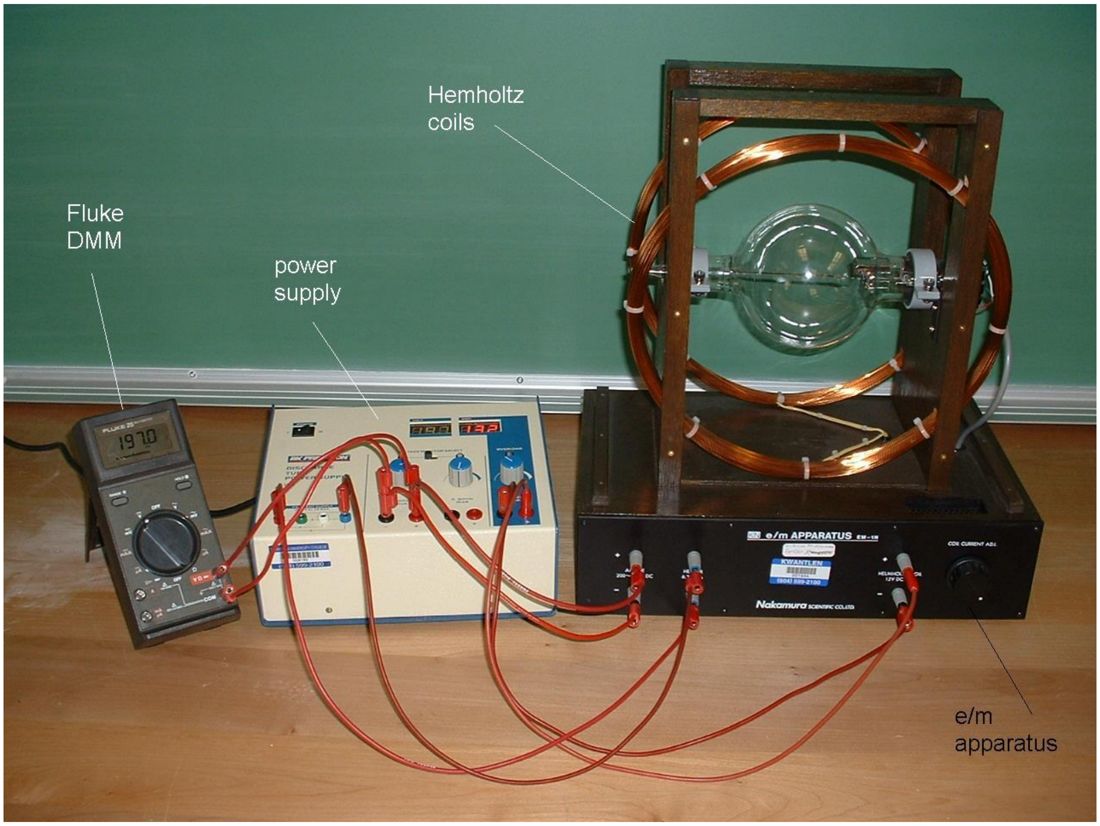

Figure 1 e/m apparatus

Attach the Fluke DMM across the 0-500Vdc jacks on the discharge tube power supply. You will measure the voltage from the DMM, as it provides greater precision than when read directly from the power supply.

The 0-20Vdc 5A MAX jacks on the discharge tube power supply provide the current *I* to the Helmholtz coils. Connect the jacks of the e/m apparatus that are labelled HELMHOLTZ COIL to the 0-20Vdc 5A MAX jacks on the discharge tube power supply (**red to red** and **black to black**).

Procedure

Caution: Do not leave the beam striking the surface of the tube for a prolonged period of time: it can take less than 3 minutes for the beam to bore a hole through and ruin the tube! Leave it deflected into a circular path, or turn off the accelerating voltage if you are not making any measurements. Also, **do not leave the power supply on at high voltages** for extended periods of time, as they tend to "burn out."

1) Set up the apparatus as described in the apparatus section. Turn the COIL CURRENT ADJ knob on the Nakamura e/m apparatus fully clockwise. The 0-20Vdc 5A MAX jacks on the discharge tube power supply provides the current *I* to the Helmholtz coils. **Do not exceed 12 V or 2 A,** since these are the maximum ratings of voltage and current for the coils. The 0-500Vdc jacks on the discharge tube power supply provide up to 500 V for the accelerating voltage, but the Nakamura e/m apparatus is rated to be accurate only for V = 200-500V.

2) Starting with V ≈ 200V, determine the current that produces a circular beam path with a diameter as large as possible (approximately 9-10 cm, but 11cm is too high for good results) so that the uncertainty of *r* will be relatively low (**the scale visible in the tube measures the diameter in cm**). Record the diameter *d* of the beam path. Choose 6-8 approximately equal increments of voltage that cover the 200-500V range and, for each V, adjust the current *I* until the beam path returns to the original diameter *d*. Record *I* and *V* each time (*I* can be read off the power supply, but use the DMM to measure *V* for the greater precision it allows).

3) Plot a graph to verify Equation (10), and determine $^{e}/_{m}$ from the graph. Note: when using scientific notation, record the value and its uncertainty to the same power, e.g., $(7.55 \pm 0.03) \times 10^{6}$ m.