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A model for evaluating the effectiveness of remote engineering laboratories and simulations in education

Jeffrey V. Nickerson [a,*], James E. Corter [b], Sven K. Esche [a], Constantin Chassapis [a]

[a] Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030, United States
[b] Teachers College, Columbia University, 525 W. 120th Street, New York, NY 10027, United States

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Abstract

Economic pressures on universities and the emergence of new technologies have spurred the creation of new systems for delivering engineering laboratories in education, in particular simulations and remote-access laboratory systems. Advocates of simulation argue that physical labs needlessly consume university space and students' time. However, proponents of hands-on laboratories argue that student engineers should be exposed to real environments. Remote laboratories have appeared as a third option. These laboratories are similar to simulation techniques in that they require minimal space and time, because the experiments can be rapidly configured and run over the Internet. But unlike simulations, they provide real data. Studying the relative effectiveness of these modes of delivering student laboratories is complex, for the underlying technology of the laboratory is just one of many possible factors that could influence effectiveness. For example, the interface to the equipment may be of importance, as might the discussions students have among themselves. This paper presents a model for testing the relative effectiveness of engineering laboratories in education that takes account of these and other factors. The results are presented for an assessment study comparing versions of remote labs versus hands-on labs in a junior-level mechanical engineering course on machine dynamics and mechanisms. The results suggest that students learned lab content infor-

* Corresponding author. Fax: +1 201 216 5385.
E-mail address: jnickerson@stevens.edu (J.V. Nickerson).

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mation equally well from both types of laboratories, and that they have a realistic understanding and appreciation of the practical advantages of remote laboratories.

Keywords: Computer-mediated communication; Presence; Educational assessment; Remote laboratories

1. Introduction

Many educators have strong feelings about the relative merits of different technologies to be used in engineering laboratories, and these educators disagree with each other. The argument is significant because it is clear that the choice of laboratory technologies could change the economics of engineering education, and it is also clear that changing the technology could change the effectiveness of education (Canizares & Faur, 1997; Ertugrul, 1998; Finn, Maxwell, & Calver, 2002; Magin & Kanapathipillai, 2000; Willams & Gani, 1992). These positions are often debated in comparing types of student laboratories that differ in their modality of delivery, namely traditional hands-on laboratories versus remotely-access laboratories versus simulations. Hands-on adherents think that engineers need to have contact with the apparatus and that labs should include the possibility of unexpected data occurring as a result of apparatus problems, noise, or other uncontrolled real-world variables. Adherents of simulation point out the high monetary, space and time requirements of hands-on labs. Setup and teardown time may be greater than the actual experiment performance time. They claim that simulation is not only cheaper, but it is also better, in that more laboratories can be conducted than with hands-on laboratories. However, there is a third alternative to be considered, namely remotely operated laboratories (Alamo et al., 2003; Gillet, Nguyen, & Rekik, 2005; Harris & Dipaolo, 1996; Henry, 2000; Nedic, Machotka, & Nafalski, 2003). They require some space, but less than a hands-on lab. They use real data, but the data is acquired through the mediation of a web interface. They are relatively inexpensive to operate.

Researchers have pointed out that the practical work of laboratories is subject to constraints. There are the constraints of physical facilities and scheduling that universities face. Also, there are constraints on what students can do; for example, students with disabilities may have less of a chance than other students to interact in laboratory environments. Thus, remote laboratories may not only satisfy the economic needs of universities, but also may be convenient for able students and an important facilitator for disabled students or students who for other reasons must take courses remotely (Colwell, Scanlon, & Cooper, 2002; Scanlon, Colwell, Cooper, & Di Paolo, 2004).

This debate over hands-on versus simulated or remote laboratories is similar to the debate surrounding rich media. As telecommunication established itself as a medium for doing business, both employees and employers became interested in telecommuting. They wondered if remote work might be just as effective as work in an office, and might be more convenient for the employee, and less expensive for the employer. Psychologists began studying how communication mediated through technology was different than face to face communication (e.g. Short, Williams, & Christie, 1976). Some researchers have presented evidence that face-to-face communication is preferred when situations are by their nature ambiguous (Daft & Lengel, 1986). Others have argued that, by increasing the fidelity of electronic communication, a sense of presence can be invoked (Schubert, Friedmann, & Regenbrecht, 2001; Schuemie, van der Straaten, Krijn, & van der Mast, 2001; Sheridan, 1992; Slater & Usoh, 1993). This literature suggests that a psychological sense of presence is not the same as actual physical presence; that is, it may be possible to feel as if one is in a particular location even if one is not. Furthermore, it can be argued that a sense of physical presence and a sense of social presence (whether the student is aware of others using the system or working on the same task) are quite distinct, and both are important to the educational effectiveness of the laboratory experience.

While some take it for granted that in remote situations higher bandwidth links will produce better communication, there is another position, that the richness of media does not matter, as people adapt to whatever media are available (Korzenny, 1978). Individuals may have a preference for face-to-face communication, but this might be socially rather than technologically determined. Nowak, Watt, and Walther, 2004 articulate this position and present evidence that, for a classroom collaboration task, mediated asynchronous video is less preferred than face-to-face, but is just as effective.

This argument has strong implications for remote laboratories. If the richness of media does not matter, then it may be that remote laboratories will be as effective as real laboratories. If the richness of media does matter, then hands-on laboratories may be superior, or remote laboratories may need to be controlled through rich interfaces. In addition, a parallel set of arguments applies to student communication. For it is possible that the interaction between students after conducting an experiment is a contributor to the students' understanding; if rich media is required for this communication, then not only the laboratory apparatus, but also the coordination technology, would need to be designed with this in mind.

In general, there are not many studies available to inform decisions by educators on the appropriate use of laboratory technology. There are, however, several notable exceptions. In an assessment of remote laboratories, researchers found that students thought hands-on labs were restrictive, in that experiments could not be easily re-run (Sicker, Lookabaugh, Santos, & Barnes, 2005). Students did like many aspects of the interactive aspects of hands-on labs; this suggests there might be a tradeoff between the concreteness of hands-on labs and the convenience of remote labs. This study and two other studies have found no significant difference in educational outcomes between remote and hands-on laboratories (Ogot, Elliott, & Glumac, 2003; Sonnenwald, Whitton, & Maglaughlin, 2003). All of these studies provide useful information to educators making curriculum decisions. However, the studies have been performed on a small number of students. As a result, they of necessity focused on only some of the variables that might reasonably be expected to affect educational outcomes.

Understanding how different technologies affect the laboratory learning experience is an endeavor which will need the participation of many researchers over many years. In this paper we seek to contribute toward this larger project by proposing a model which might define a program of assessment studies. The debate as to which type of educational lab is more effective has become an emotional argument. Part of the difficulty in resolving the debate may be the absence of a model for differentiating both the educational goals and the different technologies associated with these laboratories.

In this paper, the authors describe a model that will allow for systematic testing of educational effectiveness. The model is grounded in practice, as two of the authors have been engaged in the construction and application of remote laboratories to engineering education for the past 5 years (blinded 2003). The model provides a way to integrate the findings of streams of research in several fields that may inform our understanding of the problem. In addition, the model is designed to be used by the authors in a planned series of educational studies. The paper proceeds by first describing the technology of remote laboratories. Next, the model is described. The results of a pilot study are given, and the implications of the work are discussed.

2. Technology background

2.1. Technology architecture

Our previous research has been informed by the construction and use of remote laboratories by two of the authors over many years (Esche, 2006; Esche, Chassapis, Nazalewicz, & Hromin, 2002; Esche & Chassapis, 1998). We now describe the technology that has been constructed, for two reasons. First, for the reader that is not familiar with remote laboratories, our description will provide a context for the discussion of the assessment model. Second, the technology we describe is used in the pilot study, and so a specific understanding of the experimental apparatus may aid all readers in interpreting the pilot results.

The hardware architecture for the remote laboratory system developed at (Stevens Institute of Technology) is shown in Fig. 1. The system is based on a client–server network approach that allows the concurrent execution of multiple experiments using separate experimental setups. Multiple experiments requiring the same experimental setup are queued and executed in batch mode in the order of the incoming requests.

The laboratory is interfaced with the outside world using a Linux web server that hosts the process queue, the data input and output files generated as well as the graphical user interface (GUI). In the development of the GUI, conventional HTML pages, Java applets and CGI/Perl scripts

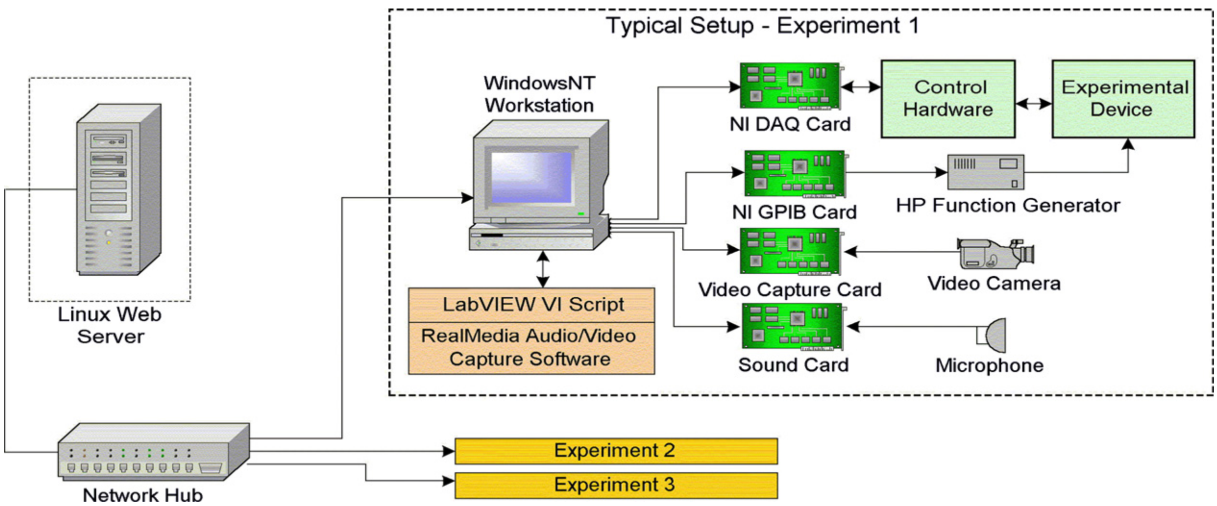

Fig. 1. System architecture of remotely accessible laboratory setups.

were utilized. The web server interacts with individual data acquisition PC terminals, which are running Windows NT and execute LabVIEW VI scripts for controlling the experiments and transmitting the experimental results back to the web server.

The software for controlling the experiments was implemented with an event-driven program structure. An endless loop idles until a user request message is received. This message is then parsed for its meaning and an appropriate sequence of functions to be performed is initiated. After completion of all actions prompted by the user request, the control program returns to the idle loop and waits for the next experimental request. We have described the technical architecture of this implementation of remote laboratories in more detail elsewhere (Esche, 2005; Esche, Chassapis, Nazalewicz, & Hromin, 2003; Esche, Prasad, & Chassapis, 2000).

2.2. Sample experiment

The one-degree-of-freedom mechanical vibration system shown schematically in Fig. 2 represents a representative example for the experimental setups implemented so far. The experimental setup for mechanical vibrations is actuated electro-magnetically. It was designed in a modular fashion, which allows straightforward extension to multiple degrees of freedom as is shown in Fig. 3.

2.3. Pedagogical use of the technology

The remote experiments are introduced to students gradually. Here we describe the three phases that the instructor leads the student through. In the first phase, in preparation for a typical remote laboratory experiment, the students are tasked with re-familiarizing themselves with the underlying physical principles, the experimental equipment and procedure of the particular experiment to be performed. Supporting background materials and online documentation are provided.

The second phase of the laboratory experience is conducted in the laboratory facility under the supervision of an instructor. In the on-site laboratory facility, the students are given the opportunity for a limited amount of direct hands-on interaction with the particular experimental setup. This on-site experimental portion is designed in such a fashion that it fits within a time period that is significantly shorter than a traditionally structured laboratory session. Thus this approach retains some – albeit brief by traditional standards – elements of a hands-on experimental experience. Furthermore, the students can seek help from the instructor at this time, thus facilitating the later execution of the remote laboratory assignment.

In the third stage, the students continue more detailed experimental studies in a remote fashion. Typically, one week is given for the student to complete the additional experimentation and write

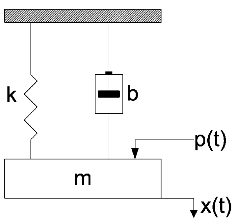

Fig. 2. Schematic of mechanical vibration system.

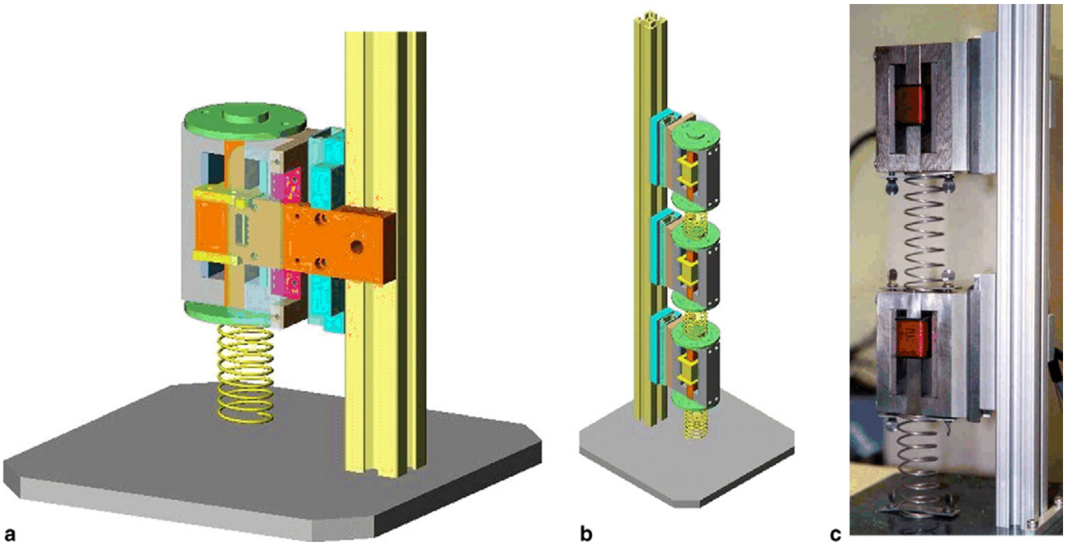

Fig. 3. Electro-magnetically actuated mechanical vibration setup: (a) schematic of one-degree-of-freedom configuration (cross-sectional view), (b) schematic of configuration with three degrees of freedom, and (c) photograph of two-degree-of-freedom configuration.

the laboratory report. The described approach leverages a limited number of experimental stations for a wide variety of studies. It also provides the students with grounding in the setup of the apparatus before they interact with it remotely.

Usage of the remote laboratories is illustrated by the following example, where the laboratory exercise was partitioned into an introductory segment to be performed on-site and an advanced segment to be completed remotely. The one-degree-of-freedom mechanical vibration setup shown in Fig. 4 can be used for various different experiments. During the on-site portion of the laboratory, the students can run a free-vibration experiment with specified initial displacement and then

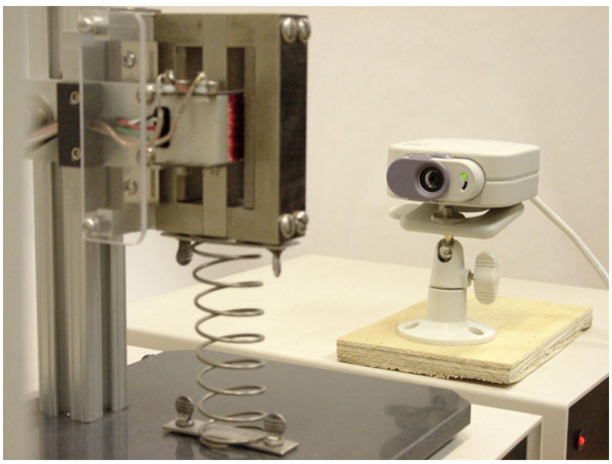

Fig. 4. Remotely accessible one-degree-of-freedom mechanical vibration setup with video monitoring.

determine the fundamental characteristics of the second-order dynamical system (for example, inertia, spring stiffness, and the damping constant) from the experimental results. All technical issues related to the setup and calibration of the system as well as the subsequent data acquisition and data post-processing can be treated in the on-site portion of the vibration laboratory. The additional benefit to be gained from other vibration experiments follows from analyzing further experimental data in response to other input signals (e.g. step response, frequency response). Thus, such experiments represent a series of repetitive experimental procedures (i.e. *select type of experiment, enter appropriate input data, collect output data, post-process output data, interpret system response*), and this part of the laboratory can be performed remotely.

Oftentimes, experiments that are carefully designed may also enable the usage of the same basic experimental setup for more advanced experimental studies. For example, the vibration system discussed and shown above allows the demonstration of an important distinction, the difference between damping due to Coulomb friction and viscous damping. Students can learn that varying the level of initial displacement in the free-vibration experiment results in either a linear or exponential shape of the envelope function for the decaying amplitudes, thus indicating which of the two forms of damping dominates the system response in the investigated amplitude range. The analysis of non-linear effects such as this most likely goes beyond the scope of a typical undergraduate course, but it can be used as a voluntary challenge problem or as part of a more advanced course, and is illustrative of the potential of remote laboratories to teach complex concepts to students who choose to go beyond the required assignments.

Having described the design and use of remote laboratories, we turn to addressing the educational assessment of these laboratories.

3. The assessment model

3.1. Overview

Remote laboratories can be used as one technology in conjunction with, or as a replacement for, other laboratory technologies. In order to guide our decision making in choosing these technologies, we need a model of how such technologies might compare with each other. The proposed model has cognitive components, in that it assumes many different factors will affect the cognition of the student, which in turn will lead to different learning results. Three types of outcomes are easily measurable. Student test scores provide strong indications of what has been learned. Of most interest are the responses to questions constructed to directly test the knowledge and skills taught in the laboratory assignment. Student grades on the actual lab assignments are also relevant. Finally, student preferences for specific labs and their associated formats and interfaces can be elicited using questionnaires.

Motivation usually turns out to be an important factor in education. It can be viewed as an individual trait, as some individuals seem to have a generally higher level of motivation for learning tasks than others. Traditionally, educators measure this difference by looking at grade-point averages, which is shown as a variable in the *individual differences* box of Fig. 5. Motivation is also a state. A student who is usually highly motivated can be bored when confronted with a particular task. This state of motivation may be influenced by other variables. For example, students

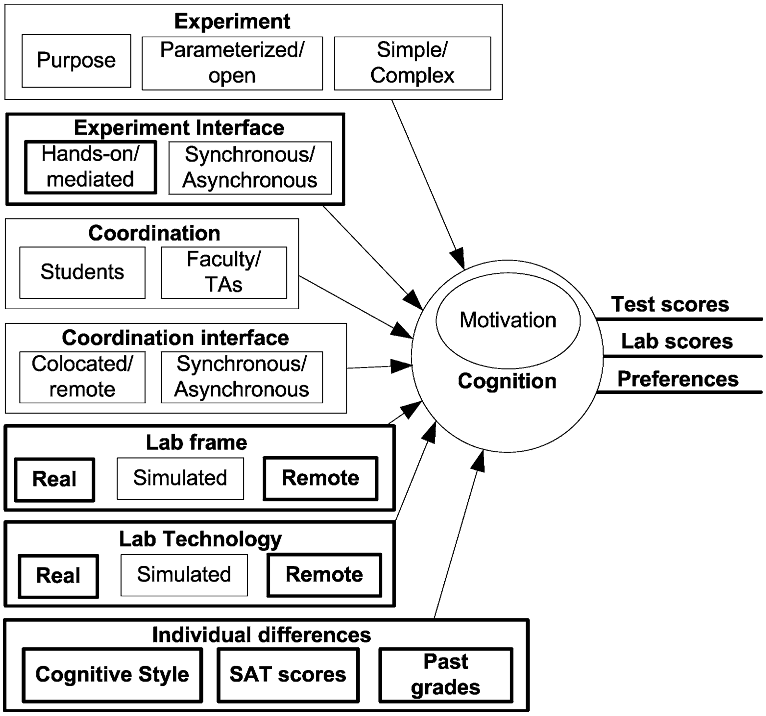

Fig. 5. A model for investigating the relative effectiveness of hands-on labs, remote labs, and simulated labs. Constructs marked with bold are manipulated in the pilot study.

confronted by simple, highly constrained experiments in which they can easily predict the outcome may be less motivated than students confronted with a complex experiment in which they are not at all sure what will happen. For environments in which students are given more latitude, researchers have pointed out that motivation is a central issue (Edelson, Gordin, & Pea, 1999; Soloway, Guzdial, & Hay, 1994), because not all students will take advantage of increased freedom.

3.2. Experiment and experiment interface

Laboratory experiments are designed for a pedagogical purpose. There are several general goals of engineering education that have been discussed by the Accreditation Board for Engineering and Technology (ABET, 2004). Several purposes applicable to student laboratories can be extracted from their broad goals:

1. An ability to conduct experiments.
2. An ability to analyze and interpret data.
3. An ability to use modern engineering tools.
4. An ability to design experiments.
5. An ability to solve engineering problems.
6. An ability to function in teams.

The technologies of the different lab modalities seem more or less appropriate for different goals. For example, if the goal is to teach students how to analyze data, then a technology which has a lower setup time is desirable, but if the goal is to learn how to use modern engineering tools, an elaborate and time-consuming setup may be part of the intended experience.

The relative *openness* of the laboratory may be a factor. McComas (1997), building on the work of Schwab and Herron (Herron, 1971; Schwab, 1964), describes four levels of openness, depending on whether the problem, the method, and the answer are given. For most labs, all three are given. The student knows what to expect, and is therefore focused on verifying an answer against a formula. The student is mainly learning how to analyze data. At the other extreme is what researchers do: the problem is open, the answer is unknown, and any method can be used.

The complexity of an experiment may have an influence on the choice of technology. It may be that more complex experiments are more appropriate to a particular type of laboratory.

A separate issue from the actual experiments is the design of the interfaces to the equipment. The authors have observed that experimentation in engineering has become increasingly mediated. For example, oscilloscopes have been replaced by displays on computers, so that the experience of turning a knob has become the experience of moving a mouse. Hands-on laboratories are often defined as laboratories in which students are in the physical presence of the equipment. However, the equipment may be controlled through a computer. In this case, it is possible that the laboratory experience mediated by a remote computer may not be so different than that mediated by a nearby computer.

Finally, the issue of synchronous versus asynchronous communication is of particular interest. With remote labs, the ability to asynchronously run the experiment is convenient from a scheduling perspective, as students can initiate a run, and later view a video of the experiment, without having to actively wait for other students to relinquish the equipment. The work of Nowak et al. (2004) in a different domain suggests that student preference will be for hands-on or synchronous experiences, but asynchronous video will be just as effective. We are interested in testing this in relation to laboratory education, as there is a design tradeoff for instructors. Real-time video will provide more direct interaction, but will also create more complex scheduling problems, as students may be in contention for devices that are to be controlled synchronously.

3.3. Social coordination and the coordination interface

When students become confused, they often attempt to alleviate the confusion by communicating with their peers, with the TA, or with the professor. Through structured interviews, the authors found that student lab groups show little variability in their strategies toward hands-on labs, but a great deal of variability in the strategies toward remote laboratories. Some student groups meet in a dormitory room and run the remote labs together. Other groups break up and run the experiments separately and then reconvene the next day to discuss the results. Students seem to prefer asking other students questions on issues they might have a problem with.

Pea argues that much, if not most, learning in science takes place through conversation, either between students or with teachers (Pea, 1993). Pea observes that laboratories are valuable because they involve tasks such as predicting, designing experiments, observing, and explaining. These tasks are part of what future engineers will engage in, and the laboratories let students engage in the tasks, and in the associated conversations. Pea showed that simulations done in groups, with instructors as facilitators, were effective in achieving learning outcomes (Pea, 1993). In general, educational research has shown that cooperative learning is a particularly effective educational strategy in science and mathematics learning (Kerns, 1996; Klionsky, 1998; Tao & Gunstone, 1999; Toumasis, 2004). This work raises the possibility that the underlying technology of the lab might be less important than the discussion about the lab among the students. In relation to coordination interfaces, it raises the question whether asynchronous communication such as electronic mailing lists can produce the benefits of conversation. For if not, remote labs might need to be augmented with capabilities for synchronized human communication as has been illustrated by Scanlon et al. (2004). Indeed, in industry, collaboration platforms are sometimes used to allow geographically dispersed teams to design 24/7 around the world. The issue is important for distance learning, where students may not be able to easily congregate in a single location.

3.4. Lab frame and lab technology

The format of the educational laboratory, whether the lab is real, simulated, or remote, may affect learning outcomes. Two possible factors are at work. The actual technology underlying the lab may affect the outcomes. However, it may be the *perceived* format of the lab that is critical – whether the student *believes* the lab to be remote or simulated. Manipulations of these beliefs are referred to in Fig. 5 as *framing* the lab format. If remote or simulated labs prove more effective than the other, it may be possible to manipulate the perception of the lab in order to see if the effectiveness is socially or technologically determined. For example, a remote lab can be described as a simulation, or a simulation as being a remote lab, and the students' preferences and scores can be observed.

3.5. Individual differences

There is some evidence that media-rich environments help higher-achieving students less than lower-achieving students (Kalyuga, Chandler, & Sweller, 1998; Mayer, 2001). Also of interest are the cognitive styles of the student. For it may be that, for example, students with a visual style of learning will respond differently to a remote laboratory than students with a verbal style. The evaluation study below was designed to include investigation of this issue, among others.

4. Pilot study

4.1. Procedure

Having described the model, we now describe a pilot study which explores the relationship of many of the variables. The evaluation study was designed and conducted as part of a course on machine dynamics and mechanisms at (Stevens Institute of Technology) during the fall 2003 semester. Students in the course were mechanical engineering majors in their junior year ($N = 29$). In this course, labs are used to deepen the conceptual understanding of the topics, and to give students practice in collecting and analyzing data and in drawing conclusions based on the data and their understanding of the issues. The main objective of the lab was to deepen students' understanding of the concepts and techniques taught in the course, by giving them experience in applying the concepts and procedures to data from real applications.

Six labs were conducted during the course. Three variants of the lab experiment (free, step, and frequency response of a mechanical vibration system) were given as remote labs, and three others were given in the traditional hands-on format dealing with rotor balancing, gear dynamics and dynamic response of high speed machinery. The two lab formats (remote versus hands-on) were compared by gathering data on student educational outcomes, and by measuring student satisfaction. In addition, the authors investigated if student preferences for and success with remote labs are related to the characteristics of individual students, in particular cognitive style and ability (as measured by SAT scores and high school GPA).

4.2. Measures

Learning outcomes were measured by exam scores and lab grades in the course. Course exams were constructed to include one or two questions on the content of each of the labs. Student satisfaction with the remote labs was assessed by a questionnaire (the Student Feedback Form (SFF)) constructed for that purpose. It also included questions evaluating specific aspects of the remote lab interface and lab procedures, and included comparable questions regarding the hands-on labs. Individual student characteristics were assessed through student records, including demographic information, Standard Aptitude Test (SAT) scores, and Grade Point Averages (GPAs).

Finally, a measure of the individual students' cognitive style, the VARK, which stands for Visual, Aural, Read/write, and Kinesthetic (Fleming & Bonwell, 2003; Fleming & Mills, 1992), was administered. This instrument measures student preferences for specific modes of communication, including visual, auditory, textual, and kinesthetic modes. A cognitive style measure was included because it is a widely accepted view in educational psychology that students' preferences vary along a verbalizer–visualizer dimension, such that they prefer to work with and learn from one type of material more than the other (Mayer & Massa, 2003). It has been argued that some students show predilections for other modes of information acquisition, such as motor or kinesthetic modes (Fleming & Mills, 1992; Gardner & Hatch, 1989). The VARK was chosen for this study because it has been used before in the context of remote labs (Amigud, Archer, Smith, Szymanski, & Servatius, 2002), and because the possibility of students being kinesthetically-oriented seems relevant to predicting student success with remote labs.

4.3. Student perceptions of remote labs

Students were asked to rate the effectiveness of remotely-operated labs (labs 1–3) in comparison to the traditional ones (labs 4–6) in providing applications of course concepts to real-world systems. Of the 26 students responding to this item, 3 (or 10%) responded "more effective", 21 (72%) "about the same", and 2 (8%) "less effective". Students were also asked to rate (on a 9-point scale) five specific aspects of the laboratory exercises (both remote and traditional) as to their value in promoting the understanding of course concepts, as shown in Table 1.

Results show that the aspects rated most important were the preparatory instructions (with a mean rating of 6.6), followed by writing the lab report (6.5). "Team work" was third (6.1),

Table 1
Importance of lab activities (for both hands-on and remote labs): means and standard deviations of student ratings

Lab Activity	Mean	Standard deviation
Preparatory instructions	6.59	1.78
Data acquisition	5.93	1.98
Lab report	6.52	2.05
Team work	6.07	2.18
Physical presence in lab	5.37	2.12

followed by data acquisition (5.9). Rated least important was "physical presence in the lab" (5.4). This low rating is another indication that students viewed the remote and hands-on labs as essentially equivalent in effectiveness. Ratings by students of the impact of each individual lab on their understanding of the course material revealed few differences between the remote and hands-on labs. The remote labs actually were rated as having slightly higher impact on average (6.1 versus 5.7 on a 9-point scale), but a close look at the data reveals that this average value has been greatly impacted by an unusually low rating that was received by one of the hands-on experiments.

The SFF also contained questions that dealt with other aspects of student experience and satisfaction with the remote labs specifically, as shown in Table 2.

The most highly rated aspects of remote labs were: convenience in access (mean rating 8.6 on a 9-point scale), convenience in scheduling (8.4), ease of use (8.4), and reliability of setups (8.2). Overall satisfaction was rated at 7.2. The lowest-rated aspect of the remote labs was "feeling of immersion", with a mean of 6.2 on the 9-point scale. These ratings show that students have realistic appraisals of the benefits and disadvantages of the remote laboratory format in general and of the particular labs implemented here. These results are consistent with answers students give to open ended questions. Students value the short amount of time it takes to run a remote lab, the convenience of being able to run the lab from where they live, and the schedule flexibility of being able to run the labs at any time.

4.4. Learning outcomes

Actual learning outcomes for the content of the remote labs versus the traditional labs were assessed by questions on the midterm and final exams directed specifically at that content. A

Table 2
Satisfaction of students with specific aspects of the remote labs: means and standard deviations of ratings

Remote lab aspect	Mean	Standard deviation
Overall satisfaction	7.15	1.17
Feeling of immersion	6.23	1.31
Ease of use	8.37	0.88
Obviousness of use	7.81	1.15
Total time required	7.89	1.67
Convenience of scheduling	8.44	1.28
Convenience in access	8.56	0.85
Clearness of instructions	7.59	1.47
Reliability of setups	8.15	0.91

composite score variable for content was constructed by summing five items aimed at the instructional content of labs 1–3 (the remote labs) and dividing by the total number of points. A composite score variable for the hands-on lab was constructed analogously for four relevant test items as well. Results revealed very similar achievement levels: the mean proportion of correct answers for the remote-lab contents was 0.60, while for the hands-on labs it was 0.61.

4.5. Individual differences in perceptions of the labs

The results reported above suggest that remote labs can be effective educationally, as students achieve equally well using these labs. But are they equally effective for all learners? Does their effectiveness vary with student ability, and/or differences in the students' cognitive style?

The authors have correlated student ability (measured by SAT scores) and academic achievement (measured by GPA) with student perceptions of, and satisfaction with, the remote labs and with educational effectiveness (see Table 3). SAT scores were marginally correlated ($p < 0.1$) with overall satisfaction ratings for the remote labs, meaning that students with higher SAT scores were more satisfied. Also, students with higher SAT scores that rated the remote labs more positively on preferences gave lower ratings to preparatory instructions. SAT scores (SAT-M, SAT-V, and SAT-total) did not correlate with any of the measures of and data acquisition. However, on the direct comparison relating to the effectiveness of the remote labs versus the traditional hands-on format, students with lower SAT score gave slightly (but not significantly) higher ratings to the remote labs.

Second, it is widely accepted that students' cognitive style can affect their preferences for educational media (Klionsky, 1998; Mayer, 2001; Toumasis, 2004), presumably including preferences for hands-on versus remote labs. Accordingly, the authors correlated VARK subscale scores

Table 3
Correlations of student ability and cognitive style (VARK) subscales with student ratings and lab-related test scores

Rating variable/score	GPA	SATV	SATM	SATT	Vark-visual	Vark-aural	Vark-read	Vark-kines	Vark-total
Effectiveness: remote versus hands-on	0.10	−0.23	−0.27	−0.26	0.21	0.46*	0.17	0.13	0.44*
Overall satisfaction	0.12	0.10	0.23	0.16	−0.03	0.13	−0.21	−0.22	−0.13
Feeling of immersion	0.18	0.33	0.24	0.35	−0.12	−0.01	−0.20	−0.21	−0.22
Preparatory instructions	−0.45*	0.05	−0.06	−0.01	−0.39*	−0.08	−0.42*	−0.33	−0.52*
Data acquisition	−0.00	0.21	0.21	0.21	−0.07	−0.09	−0.08	−0.43*	−0.23
Lab report	−0.17	0.09	−0.02	0.04	−0.21	−0.17	−0.12	−0.23	−0.39*
Team work	−0.05	0.01	−0.05	−0.04	−0.16	0.08	−0.31	−0.03	−0.36
Physical presence in lab	−0.33	0.06	0.08	0.07	−0.47*	−0.15	−0.20	−0.23	−0.44*
Remote labs test score	0.57*	0.01	−0.10	0.00	−0.15	−0.16	0.13	0.17	−0.01
Hands-on labs test score	0.32	0.29	0.39	0.39	−0.06	0.05	0.32	−0.23	0.06

Significant correlations are indicated with an asterisk.

(visual, aural, read/write and kinesthetic) with various student preference and satisfaction measures (see Table 3).

VARK subscale scores were not correlated with student GPA. The only significant correlation between VARK subscale scores and SAT scores was a negative correlation between a kinesthetic style and SAT-verbal score. This general lack of significance means that VARK scores are not simply surrogates for ability or achievement. The correlations between the cognitive style (VARK) subscales and the importance ratings for specific lab activities showed that students with a kinesthetic style also gave lower importance ratings for the value of preparing lab reports and for team work.

Those with a visual style gave lower ratings to the importance of the preparatory instructions and to the importance of physical presence in the lab. Those with read/write cognitive style as measured by the VARK also gave lower ratings to the importance of the preparatory instructions.

No significant correlations were observed between the cognitive style measures and learning outcomes as measured by the respective content scores. Not surprisingly, GPA and SAT scores were all positively related to the overall test score on hands-on lab content. Interestingly, though, test score on the remote-labs content was related only to GPA but not to SAT scores. GPA is a measure of academic achievement, which is seen as strongly affected by student motivation, whereas the SAT is a measure of aptitude. Thus, this pattern of correlations might suggest that learning in remote labs requires higher levels of student motivation.

It should be noted that only a few of the correlations in Table 3 are significant, therefore it is prudent to worry about the possibility of Type I error. Thus, any inferences about relationships among variables resulting from this correlational analysis should be viewed with caution and replicated if possible.

4.6. Discussion

The results of this pilot assessment study seem encouraging to advocates of remote laboratories. More than 90% of the student respondents rated the effectiveness and impact of the remote labs to be comparable to (or better than) the hands-on labs. This equivalence was also demonstrated by analyses of scores on exam questions involving specific lab content.

Results involving the relationship of specific student characteristics to rate aspects of the remote lab format were inconclusive. There is some tendency (though not significant) for lower-ability students to give slightly higher ratings to the remote labs. Total VARK scores (claimed to measure comfort with multiple modalities of information) did predict higher ratings of effectiveness for the remote labs, and also predicted a lower rating of the importance of physical presence in the lab (as did the visual style subscale score). This suggests that remote labs may be especially appropriate for students possessing a highly visual or highly flexible learning style.

5. Future research

It may be that students with a strong imagination can envision an experiment better, and therefore feel less of a need to be physically present to see it actually happen. While this might be true for simplified experimental setups, it would be prudent to test the correlation with increasingly complex equipment. Furthermore, it would be interesting to discover if such students also show more comfort with *Gedanken* or thought experiments (e.g. Kalyuga et al., 1998).

More research is planned to replicate these results with a broader range of topics and tested skills. The authors intend to further investigate how student characteristics affect their satisfaction with remote labs (and simulations) using larger samples, and to test the impact of distinct features of the interface. In the area of cognitive styles, the authors plan to more thoroughly investigate the role of visual preferences and visual abilities; for example, it may be that both visual style and spatial ability influence a student's learning with or preferences for remote labs versus hands-on labs (Kozhevnikov, Hegarty, & Mayer, 2002; Mayer & Massa, 2003).

More research on coordination is also planned. Learning in laboratory settings, in both education and in industry, is usually a group activity. The use of different technologies may change the way students interact with each other. This in turn may change the educational outcomes. For example, remote laboratories allow for individual students to interact with apparatus that in the past would have been manipulated only as part of a group. Students interacting individually with the apparatus are still inclined to share their experiences with other students, and to ask questions of instructors. Understanding how the technologies affect social learning patterns might be important in understanding the impacts of the technology. Such an understanding might also lead to the design of different forms of interaction that can increase educational effectiveness. We described a way of partitioning laboratory exercises into a sequence of activities that mix laboratory technologies. In the future we plan to study ways of mixing coordination processes and technologies into the educational approach.

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.

6. Conclusion

The authors have outlined a model for testing the relative effectiveness of hands-on, remote, and simulated laboratories. This model may form the basis for future research which will be useful for educators seeking to understand how a choice of laboratory technology may affect educational outcomes. The model draws attention to the role of coordination, as student's sensemaking processes may play a role in what they learn from laboratory experiments, regardless of the technology used.

We have also discussed results from a pilot assessment study that directly compared remote and hands-on labs in the context of a single course. This focused comparison, though limited in scope, allowed for carefully controlled comparisons of the two lab formats, because exactly the same students took part in both types of labs. The results suggest that remote labs are comparable in effectiveness to hands-on labs with respect to the educational objective of teaching students to solve problems based on concepts taught in the course.

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