Constructing Reality: A Study of Remote, Hands-On, and Simulated Laboratories

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Laboratories play a crucial role in the education of future scientists and engineers, yet there is disagreement among science and engineering educators about whether and which types of technology-enabled labs should be used. This debate could be advanced by large-scale randomized studies addressing the critical issue of whether remotely operated or simulation-based labs are as effective as the traditional hands-on lab format. The present article describes the results of a large-scale (N = 306) study comparing learning outcomes and student preferences for several different lab formats in an undergraduate engineering course. The lab formats that were evaluated included traditional hands-on labs, remotely operated labs, and simulations. Learning outcomes were assessed by a test of the specific concepts taught in each lab. These knowledge scores were as high or higher (depending on topic) after performing remote and simulated laboratories versus performing hands-on laboratories. In their responses to survey items, many students saw advantages to technology-enabled lab formats in terms of such attributes as convenience and reliability, but still expressed preference for hands-on labs. Also, differences in lab formats led to changes in group functions across the plan-experiment-analyze process: For example, students did less face-to-face work when engaged in remote or simulated laboratories, as opposed to hands-on laboratories.

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1. INTRODUCTION

Most science and engineering educators believe that the hands-on experience of the science laboratory is a necessary supplement to the relatively passive experiences of reading textbooks and listening to lectures that comprise a large part of the student experience in universities. This belief in the value of hands-on work is backed up by theories of instruction, for example, in the ideas of inquiry learning [Edelson et al. 1999], "anchored instruction" [Bransford et al. 1990], and by basic principles of constructivism [Lave and Wenger 1990; Pea 1994]. Furthermore, the lab groups created in a typical science course constitute a traditional practice that might now be described as a form of cooperative learning (compare with Johnson and Johnson [1999] and Kerns [1996]).

However, students have mixed opinions about the value of laboratories in science and engineering courses. In some cases, laboratories are perceived as beneficial, but in others they are seen as too easy or time consuming for the educational result achieved. University administrators have a different set of issues related to laboratories. Laboratories encumber both space and schedules. The equipment is oftentimes costly, and needs to be maintained. Also, in the economically-driven push toward web-based education, the traditional practice of hands-on physical laboratories becomes impractical or unfeasible for distance learning courses.

For several decades, researchers have explored the use of information technologies to augment the laboratory experience, such as through use of simulations. For example, the Smalltalk language was inspired by the language Simula, and constructed in order to offer the potential (even for young children) to learn in artificial worlds [Goldberg 1984; Kay 1977; Kay and Goldberg 1977]. While simulations have been widely adopted in education, many if not most educators feel that they lack an important pedagogical characteristic. Simulations are not real, while hands-on laboratories are. For students, confronting the physical reality corresponding to book-learned theories can be an important experience.

Recently, the ubiquity of standard web interfaces and the presence of shared infrastructure such as the Grid [Foster et al. 1999] across universities have made possible the creation of a third kind of technology platform, called a remote laboratory. This technology blends aspects of the physical and virtual. Remote laboratories are similar to hands-on in that they are part of the real world. The experiment actually takes place, and the data reflects interactions between physical devices, not virtual entities. On the other hand, remote web-accessible laboratories are similar to simulations in that the student does not have to be colocated with a particular piece of laboratory apparatus. The experiments are often run from dormitory rooms; students use the Internet to remote-control the apparatus. The student can pick the time to run the experiment, and as in a simulation may be able to run the lab procedure multiple times, thereby exploring the space of potential results by varying the experimental parameters. No student time is needed to set-up or tear down the apparatus.

While there are many advocates of remote laboratories, there are also staunch advocates of hands-on laboratories who see both simulations and remote laboratories as potentially harmful to students by depriving them of important learning experiences. It seems clear that in many scientific fields we should not graduate scientists or engineers who have never performed a hands-on experiment. But in some fields, experiments are highly mediated: Scientists interact with particle accelerators through computer interfaces. Nevertheless, defenders of hands-on labs would argue that there is a long educational road before one gets to the particle accelerator, a road which should be filled with hands-on experiments that build scientific intuition.

No one disputes that experiments are important. Laboratory experiences seem necessary in order for students to become expert practitioners of science. Also, there is evidence that the inclusion of labs in a science curriculum raises achievement at both the high school and college level [Freedman 1997; Magin et al. 1986]. There is not, however, widespread agreement as to the ideal characteristics of these laboratory experiences. Perhaps this is because labs can serve multiple educational goals. For example, the *Accreditation Board for Engineering and Technology* [ABET 2005] has proposed a set of objectives for the use of laboratories in engineering education. These objectives make clear that laboratories can enable the assessment and improvement of a range of student competencies. Some of these educational objective skill areas, such as psychomotor skills and sensory awareness, seem to presume hands-on laboratories. However, most of the listed objectives (e.g., data analysis, communication, teamwork) apply both to traditional hands-on labs and to remote or simulated labs.

Some of the disagreements as to the ideal characteristics of educational laboratories, as well as specific questions about the effects of introducing technologically-enabled labs, might be resolved by better empirical data on what makes such labs effective. However, to-date there have been no large randomized studies which examine what happens in the laboratory portion of the educational process when alternative lab technologies (e.g., hands-on, remote, or simulated) are used, and how these technologies might affect learning outcomes. The present study is a step in this direction.

Our research questions are as follows. First, are remote labs and simulations as effective as traditional hands-on labs in promoting understanding of the specific lab topics? Second, is there a relationship between student characteristics (especially general and spatial ability) and learning effects? Third, what aspects of remote labs and simulations are judged advantageous and disadvantageous by students? Finally, do student learning-related behaviors (including lab group interactions) differ for remote labs and simulations, as compared to hands-on labs?

The results of this study should particularly interest educators who are faced with curriculum design and implementation issues in which economic pressures and learning goals are potentially in conflict. There is also a broader significance. The way people function in scientific careers, in both industrial and academic settings, is often mediated through computing technologies. The wider adoption of robotic devices, webcams, and simulators will only accelerate this trend. Thus, answering the preceding research questions may shed some light on the positive and negative impact that mediation may be having on our professional practice.

First, we will review relevant literature in the area. Following this, we will describe the physical devices used in the study. Then we will discuss the design of the study, and report the obtained results for 306 freshman engineering students. Finally, we discuss the theoretical implications of the work in relationship to computer mediation, as well as the empirical implications of the study for science and engineering educators.

2. BACKGROUND AND RELATED WORK

A survey of educational laboratory research done in 1982 concluded with a call for more empirical research using agreed-on outcome measures and larger sample sizes. The authors reprised their work in 2004, and found that little had changed [Hofstein and Lunetta 1982, 2004]. A 2006 survey which focused on remote and simulated laboratories also found few large-scale empirical studies [Ma and Nickerson 2006]. There are many reasons why there have been relatively few educational evaluations of labs. The newer technologies are built by engineers and scientists who usually write about technical design matters, rather than educational evaluation issues. Even if there is a desire to evaluate the new technologies, comparing the new labs against alternative strategies is not always easy, given their different qualities. Also, the laboratory equipment may be inherently specialized, which means few students will be prepared to use it in any given semester. Thus, the studies that are done usually have small sample sizes.

There are, however, many articles which offer opinions about the comparative advantages and disadvantages of new technologies in engineering education (e.g., Canizares and Faur [1997]). Some of these articles claim that expense pressures are causing schools to use new technologies, regardless of their pedagogic value. In other words, change is inevitable. There is also a set of opposing articles, many polemic in tone, that defend hands-on laboratories (e.g., Finn et al. [2002]). We can infer that educators feel strongly about the issue, even without performing evaluations.

With regard to remote laboratories, there are now many implementations scattered across the world, as well as a wealth of descriptions of the devices and how they are used in courses [del Alamo et al. 2003; Gillet et al. 2000; Henry 2000]. These reports are unrestrainedly optimistic about the prospects for the technology. The labs themselves have been surveyed and their features compared (e.g., Amigud et al. [2002] and Nedic et al. [2003]). These reports document that there is a general trend toward more labs with increasingly elaborate interfaces. However, few if any studies have evaluated the technologies' educational effectiveness. Although there is some anecdotal and statistical evidence demonstrating that remote and simulated labs are as or more efficient than hands-on labs from a functional or economical perspective, few evaluations have been performed on whether they are also such from an educational standpoint [Amigud et al. 2002]. In the evaluations that have been performed, the outcome measure is usually *student preference*: Papers which focus on building the experimental apparatus often discuss the students' course assessments (e.g., Albu [2004], Arpaia et al. [2000], and Hoyer et al. [2004]). But student preference does not tell us how much and what types of learning took place.

Some think that laboratories should be used to teach scientific inquiry (e.g., Hegarty [1978]). Consistent with this, a small number of studies have focused on *exploratory learning*. Students are expected to rediscover basic physical theories. For example, three teachers-in-training were observed working with hands-on and simulated labs: The teachers had a hard time recreating theories in either lab setting, even though two had physics backgrounds [Marshall and Young 2006]. However, the exploration went faster in the hands-on case. Simulations caused teachers to focus on quantitative output, whereas hands-on work led to a natural plan-test-theorize cycle. Moreover, students became mistrustful of the simulation when it produced an unexpected result. These observations critical of simulations echo earlier work which suggested that simulations are cumbersome [Roth et al. 1998]. There are, however, other studies which have demonstrated that they can be effective [Boroni et al. 1997; Pea 1993; Windschitl and Andre 1998; Zacharia and Anderson 2003; Schwartz and Black 1996]. Furthermore, the graphs that computers provide can aid conceptual understanding in laboratory settings [Russell et al. 2004].

The most thorough evaluation of *conceptual learning* in relation to remote laboratories is a study by Sonnenwald et al. [2003], which showed that remote laboratories are just as effective as hands-on. The study used graded reports as well as participants' preferences. It also paid attention to and built interfaces for group processes. The authors concluded that students compensate for the failings of different technologies. Other studies have also shown that differences in learning in one versus another lab environment are not significant [Corter et al. 2004; Nickerson et al. 2007; Ogot et al. 2003; Scanlon et al. 2004; Sicker et al. 2005].

Some previous studies of new technologies have been based on the theory of situated cognition [Brown et al. 1989; Kirshner and Whitson 1997; Lave and Wenger 1990; Winn 1993]. Some have looked at the potential role of technology as a focus for collaboration among students; they argue that learning takes place through sense-making activities on the part of students, and that the technology can form the locus of group interaction [Edelson et al. 1999; Pea 1993; Reiner et al. 1995]. These studies invert the normal emphasis found in laboratory literature: The focus is on group interaction, not the technology. The simulations are important because they facilitate group interaction, but learning comes from the students' interactions with each other and the instructors.

Because our prior research has convinced us that collaborative learning is a critical aspect of the benefits of educational laboratories, we now turn to look at studies which are not about laboratories per se, but about the way groups collaborate remotely. Hands-on labs are conducted in a particular time and place, requiring face-to-face interaction, while remote labs and simulation permit many other possible group interactions. Students can still gather to perform simulations and remote labs, or collaborate simultaneously from separate locations. Further, they have the option to collaborate asynchronously.

Organizational studies assume that distance is a factor in collaboration, but there is not a consensus on how important it is. Greater physical distance between team members is associated with greater behavioral and management challenges, which in turn can lead to lower team performance [Cummings and Kiesler 2005; McDonough et al. 2001]. On the other hand, virtual teams can generate more solutions and take less time to reach a consensus than colocated teams [Karan et al. 1996; Schmidt et al. 2001]. Furthermore, distance may be important to attitudes. For example, the experiments of Bradner and Mark [2002] manipulated beliefs and showed that subjects held a more negative attitude toward those believed to be far away rather than close. Thus, we may expect to see distance at least influencing the attitudes of students.

Distance may be just one of many factors affecting group work. For example, the common experiences of a team, the way work is coupled, the incentives to collaborate, and the technology at hand are all factors that influence collaboration results, and in proper combination can help mitigate the negative effects of distance [Olson and Olson 2000]. This implies that a group of students with a set of common experiences who find a loosely coupled way of handling experiments may be able to work better with remote technology than a group with different work processes. Mayer [2001] argued that humans can and do adapt to different technologies. Even crude, media-poor technologies can be as effective as refined, media-rich ones because people will adapt their work patterns and interactions to the available media capabilities. If this is so, we might expect to see students communicating effectively with their peers, or even their instructors, using technologies such as online chat.

Finally, the constructivist position suggests that there is another important factor in how collaboration proceeds: participation. Evidence suggests that spectators learn less than performers [Stamovlasis et al. 2006]. This suggests that we should pay particular attention to the level of participation of students in relation to the different technologies.

In summary, previous research provides support for the following hypotheses: that in terms of learning outcomes, remote laboratories will be as effective as hands-on, as will simulations. Furthermore, we expect that students will adapt their working patterns to the new technologies, and that new patterns of social and collaborative processes may arise in the lab groups for remote and simulated labs. Thus, as part of our study we not only want to look at the relative effectiveness of different types of laboratories, but also to try to understand the behaviors and attitudes of the students using them.

3. THE APPARATUS

3.1 Overview

Because we believe that the actual interfaces to the equipment may have an impact on its educational effectiveness, we present here a brief explanation of

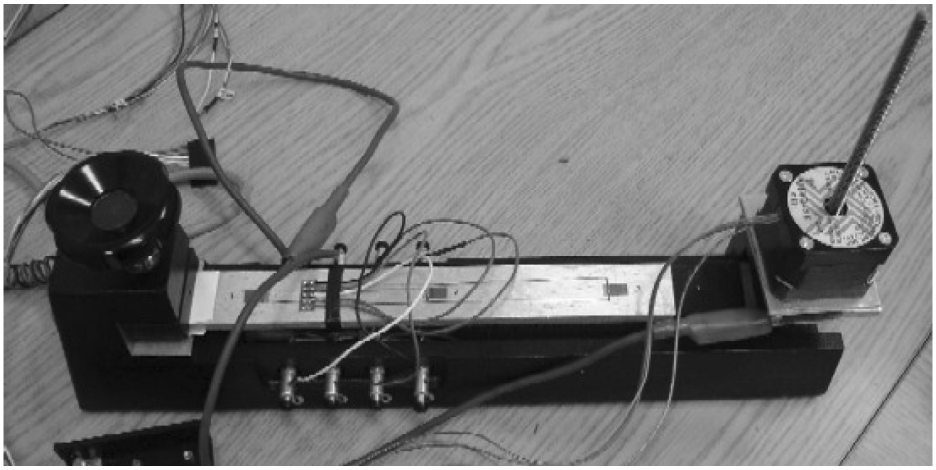

Fig. 1. Cantilever beam without stress raisers.

the technology. Interested readers may interact with some of the technology through a publicly available website [Esche 2004]. The overall architecture of the system has been explained in detail elsewhere [Esche 2005; Esche et al. 2003]; here we focus on describing the remote laboratory apparatus and simulation used in the study.

3.2 Remote Laboratories

We will discuss two beam experiments: a simple one and a more complex one with a perforation in the beam. The perforation operates as a stress raiser.

The first apparatus is a plain cantilever beam as shown in Figure 1. The experiment using this device studies a uniform cantilever beam that is rigidly clamped at its fixed end and deflected by a single point load on the beam centerline near the free end, as shown in Figure 1. Three strain gauges were installed at equal intervals along the axis, also of the beam as shown in the figure. The purpose of this experiment is to determine the shear force and load from strain measurements, to verify the linearity of the strain along the beam axis, and to confirm the shear force and moment relationships by comparing two different stress measurements with theoretical predictions.

The experiment is conceptually complex, involving a variety of concepts that freshmen are just beginning to master, and in our observations of the laboratories we noticed that students are actively struggling to master the ideas.

The second apparatus is an elastic cantilever beam with a stress raiser in the form of a perforation. The purpose of this experiment is to demonstrate the existence of stress concentrations in the vicinity of a geometric discontinuity (in this case, a circular hole on the beam centerline) in a cantilever beam and to obtain an approximate measure of the elastic stress concentration factor K. For measuring the stress concentration, three strain gauges were installed for measuring the varying strain field in the transverse direction near the hole.

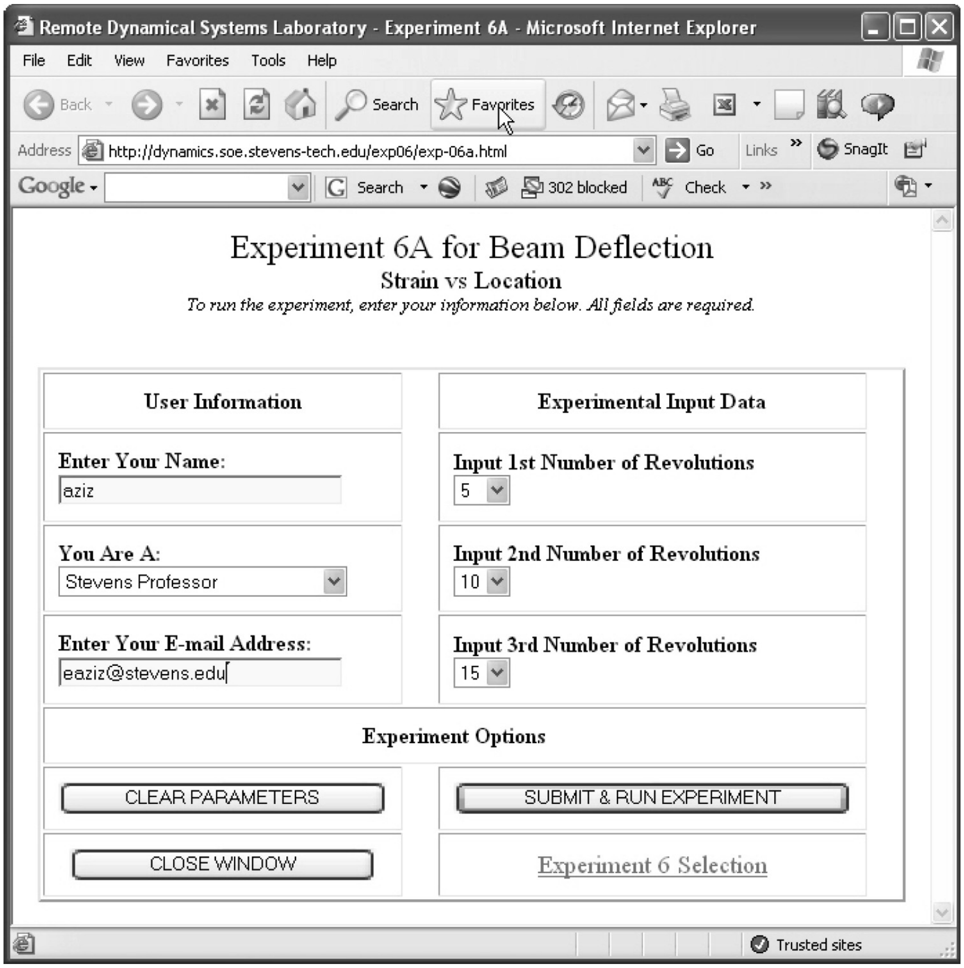

Fig. 2. Remote laboratory input panel for cantilever beam system.

In the experiment using the uniform beam, the student can input three different displacement values at the free end of the beam, as shown in Figure 2. After filling out the input form and running the experiment, the student is able to view the results either from the website or through a link sent to the email address that the student has provided.

As shown in Figure 3, the experimental results include the strain gauge factor *GF*, the distance of each strain gauge from the point of load application, the zero-load output voltage *VZ*, and the load output voltage *VL*. A video file showing the beam deflection experiment in action is also included in the results. We do not show here the perforated beam; the apparatus and interface are similar.

Notice that the current remote lab interface cannot be used to run experiments in real time; rather, students view the results of an experiment a short time after it has been run. The design tradeoff was made between providing

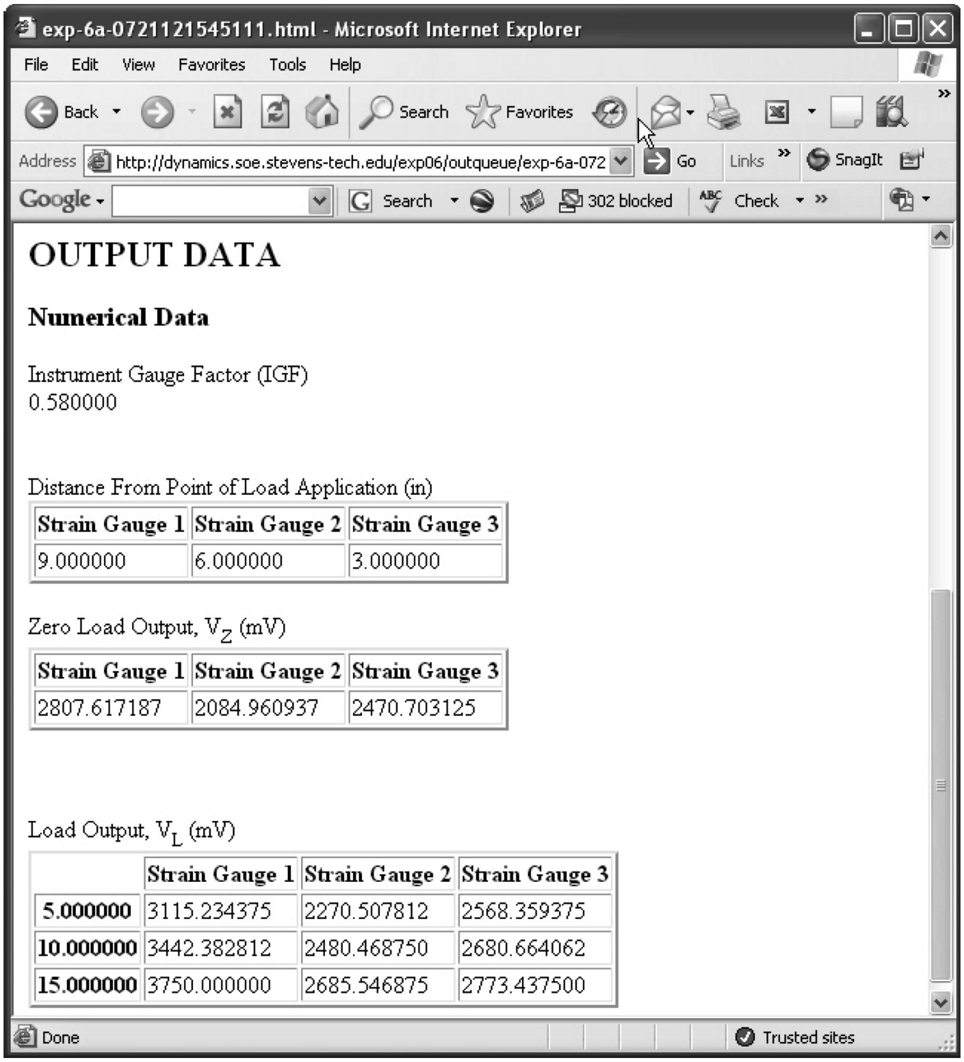

Fig. 3. Experimental output page.

real-time interaction, but forcing fixed scheduling on the students, or providing asynchronous interaction with flexible scheduling. Asynchronous interaction was selected. The more general point is that the remote laboratory technology used here is not the highest-fidelity nor the most interactive interface possible, and it may be that improvements to the interface, as suggested by many students, could raise its educational effectiveness beyond the results reported in this study.

3.3 Simulations

The simulation, shown in Figure 4, was built to closely match the apparatus used in the remote laboratory. In order to make use of some of the design

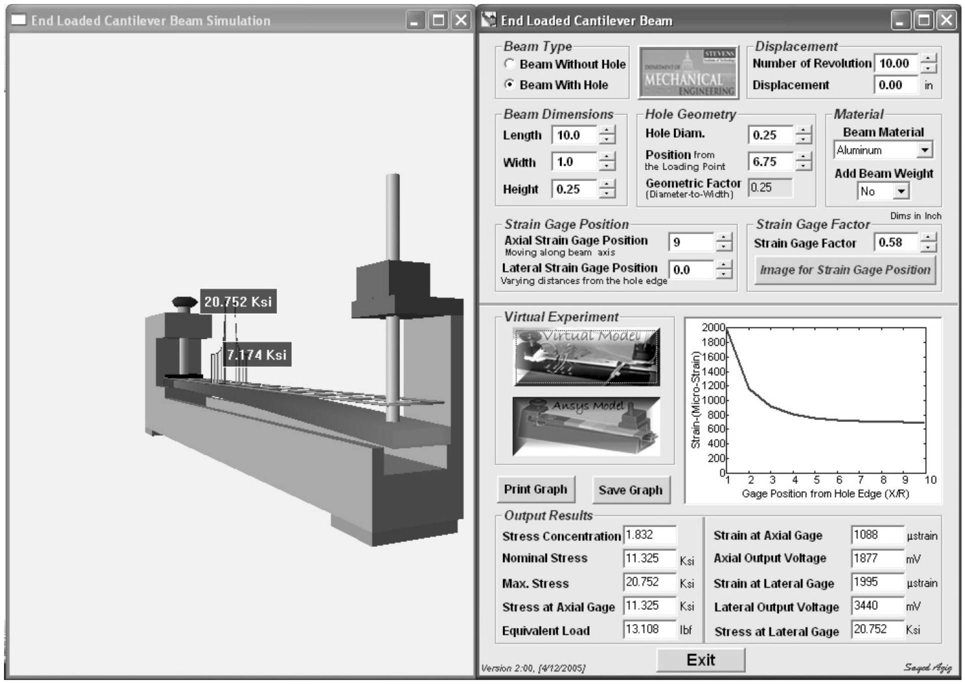

Fig. 4. Stand-alone cantilever beam simulation.

freedom inherent in simulations, we provided functionality which was impossible to achieve in either hands-on or remote laboratory settings. For example, in the simulation, stress and strain values in the beam are color coded, so that students can dynamically see the results of changing experimental parameters. Students can also instantly change the material of the beam as well as the geometry and location of the stress raiser, something that cannot be done in real experiments.

Unlike the remote laboratory, the simulation interaction is run in real time, and students can freely change their viewpoint as they observe the image of the apparatus.

4. METHOD

4.1 Participants and Context

Participants were 306 students in a single undergraduate engineering course taught in the spring of 2005 at a large school of engineering in the Northeast. The course, Engineering and Design II, is a required core course in the engineering curriculum. It is tightly linked with another course, Mechanics of Solids, and includes design projects plus a number of lab experiences designed to illustrate the concepts taught in the lecture course. Structurally, the course is divided into 14 lab sections taught by separate instructors (though a few instructors taught more than 1 section). Within each lab section, the students were divided into lab groups (teams) with 3–4 members each. The students were allowed to self-affiliate in forming these lab groups, with other students being formed into teams by the instructor.

4.2 Measures

The primary measure of knowledge gains was a brief multiple-choice test on two relevant lab topics (described next). Students also completed a lab preferences questionnaire designed to gather information on student perceptions of the lab content, format, and team interactions for the relevant labs.

In order to investigate how individual student characteristics such as ability might affect student perceptions, learning, and behavior in the labs, data on individual student GPA and SAT scores was obtained from student records and matched with the data from participant questionnaires and tests. Also, information on individual students' visualization skills was collected via standardized tests of spatial ability, administered in a prerequisite course in the previous (fall 2004) semester. These consisted of the paper folding, card rotation, and surface development tests from the *Kit of Factor-Referenced Cognitive Tests* [Ekstrom et al. 1976].

Learning outcomes were measured with a four-item multiple-choice test given after the relevant labs. Two items on this quiz concerned simple beams and two concerned perforated beams.

4.3 Procedure

2 specific lab experiments were prepared in each of 3 delivery formats: as traditional hands-on, remote-, and simulation-based labs. The labs were on 2 related topics: Topic 1 concerned strain on a simple beam, and topic 2 that on a perforated beam. Each of the 14 lab sections in the course was randomly assigned to 1 of 4 conditions: In the first condition (HandsOn-Remote) students experienced lab topic 1 in the hands-on format and topic 2 as a remote lab; in the second condition they experienced topic 1 in the remote-lab format and topic 2 as a hands-on; in the third condition topic 1 was hands-on and topic 2 was a simulation; and students in the fourth condition experienced topic 1 as a simulation and topic 2 in the hands-on format. For ease of reference we refer to the first 2 conditions as the remote lab conditions and the last two as simulation conditions. The experimental design is summarized in Table I.

In the course, the lab for topic 1 (simple beam) immediately preceded that for topic 2 (perforated beam). The content-related instructions given for hands-on, remote-lab, and simulation versions of these two labs were identical, but some additional specific instruction in using the remote lab and simulation software was necessary. The instructors provided short demonstrations of the interfaces to orient students prior to their first experience with the technology.

In the class immediately following the perforated beam lab, students were given the knowledge test. Incentives were offered for completion of the lab preferences questionnaire because completion of that instrument could not be considered a normal part of the course requirements. Students who completed and turned in the questionnaire were offered a gift certificate for a free drink

Table I. Design of the Experiment

Lab Condition	Lab Section Label	No. of Students (total)	Topic 1: Beam	Topic 2: Perf Beam
Remote conditions	E1	24	Hands-on	Remote
	E2	22	Hands-on	Remote
	E5	24	Hands-on	Remote
	D	22	Remote	Hands-on
	K	22	Remote	Hands-on
	E3	22	Remote	Hands-on
	E4	20	Remote	Hands-on
N	7	156		
Simulation conditions	A	25	Simulation	Hands-on
	C	23	Simulation	Hands-on
	I	23	Simulation	Hands-on
	B	23	Hands-on	Simulation
	F	19	Hands-on	Simulation
	G	15	Hands-on	Simulation
	H	22	Hands-on	Simulation
N	7	150		

Table II. Subtest Scores (reported as percentage correct) on the Knowledge Test, by Topic and Condition

	Topic 1: Simple Beam			Topic 2: Perforated Beam		
	Mean	Std. Dev.	N	Mean	Std. Dev.	N
Remote Lab Conditions:						
Hands-on-Remote	46.9	35.2	65	32.3	34.7	65
Remote-Hands-on	54.8	36.3	83	36.7	26.0	83
Simulation Conditions:						
Hands-on-Simulation	42.9	33.9	78	34.6	32.5	78
Simulation-Hands-on	52.3	34.4	66	30.3	28.9	66
TOTAL:	49.3	35.2	292	33.7	30.5	292

at a popular neighborhood coffee shop. 208 students fully completed the lab preferences questionnaire.

5. RESULTS

5.1 Learning Outcomes

Descriptive statistics for scores on the postlab knowledge test are shown in Table II, separately by condition. The four experimental conditions were: Hands-On-Remote, Remote-Hands-On, Hands-On-Simulation, and Simulation-Hands-On. Scores are reported as percentage correct, separately for each of the two lab topics: the simple beam and perforated beam. It can be seen that the knowledge test for the perforated beam experiment was more difficult than for the simple beam (33.7% correct versus 49.3% for the simple beam subtest). In order to facilitate comparisons among the conditions, the mean scores are plotted in Figure 5 as deviation scores (with the subtest mean score across all conditions subtracted out).

Knowledge test scores were analyzed in a repeated-measure ANOVA, with the four experimental conditions as a between-subjects factor and topic as a

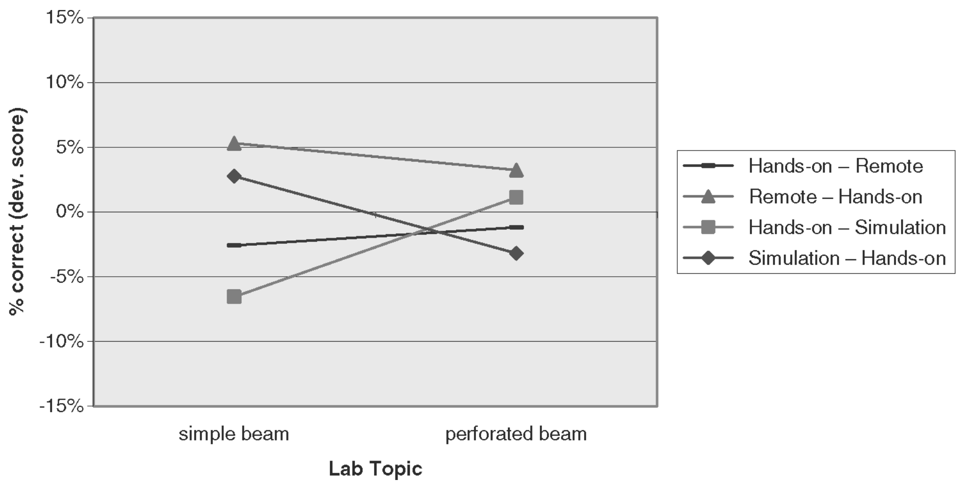

Fig. 5. Knowledge subtest scores (percent correct, expressed as deviation scores) by lab topic and experimental condition.

within-subjects factor. Experimental condition groups did not differ significantly in score: $F(1,288) = 1.35$, $p > .05$. This means that participants did not score higher or lower depending on the *sequence* of lab formats that they encountered. Mean scores did differ between the two lab topics ($F(1,288) = 35.61$, $p < .05$) because scores on the perforated beam lab test were lower than those on the first lab topic, the solid beam.

Regarding the main research question on the effects of lab format on lab test scores, inspection of Figure 5 reveals that on the first lab topic (i.e., strain on a simple beam) knowledge scores were highest for students in sections performing this experiment in remote lab format, and next for those performing the lab as a simulation. The lab test scores of students experiencing this first topic as a remotely operated lab were compared to the mean scores of the two sections experiencing the lab in traditional hands-on format by a test of a simple-effects contrast. This test was significant: $t(290) = 2.058$, $p < .05$ (2-tailed). The analogous test comparing scores (on the simple beam experiment) of students in the sections who performed this lab in simulation format to those experiencing the lab in traditional hands-on format was not significant: $t(290) = 1.473$, $p > .05$ (2-tailed).

This pattern of test scores for the first beam experiment that students encountered was not replicated for scores on the second lab topic (strain on a perforated beam). As can be seen in Figure 5, the scores of students experiencing this second lab topic in remote or simulation format had means of intermediate magnitude between the scores of the two groups who experienced this second topic in traditional hands-on format. Analogous t-tests comparing these remote lab scores to those of students experiencing the same topic in hands-on format, as well as the test comparing mean scores in the simulation condition to hands-on scores, found the results were not significant, suggesting that there are no real differences among the groups for this second lab topic.

However, it is perhaps not surprising that participant scores on test items relevant to the second lab topic do not differ significantly. After all, at this point in the course all participants have experienced one beam lab in traditional hands-on format and one in nontraditional (remote or simulation) format. If there is significant carry-over of conceptual understanding gained in the first (simple) beam experiment to the second (perforated) beam experiment, then differences among the four experimental conditions in test scores for this second perforated beam lab would be expected to be minimal.

Furthermore, the scores of students in the remote/hands-on condition are the highest of any experimental group for *both* lab topic subscores (see Figure 5). This observation, too, is consistent with the hypothesis of knowledge gain carry-over between the simple and perforated-beam experiments. An obvious alternative explanation for this pattern is that students in the remote/hands-on condition were simply more capable than other groups of students *to begin with*. However, this seems unlikely, since in this experimental design lab sections were *randomly* assigned to conditions. Nevertheless, to check this alternative explanation we ran new analyses, controlling for effects of preexisting student ability. Specifically, we reran the t-tests described earlier as analyses of covariance [Pedhazur 1982] with cumulative grade-point average (GPA) for each individual student as the covariate. Results of these analyses were nearly identical to those reported before for the simple t-tests. Scores of students on the (first) simple beam experiment were significantly higher for those experiencing the remote lab version compared to those experiencing the lab in traditional hands-on format ($t(283) = 2.225$, $p < .05$), while the covariate (GPA) had a marginally significant effect on scores ($t(283) = 1.804$, $.05 < p < .10$). Scores were also higher for those experiencing the simulation-based lab compared to those experiencing the lab in traditional hands-on format, but this difference was only marginally significant ($t(283) = 1.776$, $.05 < p < .10$), as was the effect of the covariate (GPA), with $t(283) = 1.910$, $.05 < p < .10$. As in the previous analyses, test scores for the second lab topic, namely, the perforated beam experiment, did not differ significantly among conditions when controlling for GPA.

This knowledge test data is actually multilevel in the sense that individuals and their knowledge scores are nested within lab group and lab section within the course. Lab section and instructor effects cannot be distinguished because only a few instructors taught more than one section. Accordingly, we conducted hierarchical linear modeling on the total test scores to see if these hierarchical sources of variance needed to be included in the model. We found that *lab section* accounted for only a small proportion of variance in total knowledge test score (ICC = .06), as did *instructor* (ICC = .03). However, *student lab group* accounted for a large proportion of the variance (ICC = .32). This finding is intriguing because it suggests that what goes on in lab groups has a large impact on knowledge gains in lab-related content. One possible alternative explanation is that student ability is relatively homogeneous within lab groups and heterogeneous between them because students in this course had the opportunity to self-affiliate into these groups. However, this explanation can be discounted because a hierarchical linear model testing whether student ability

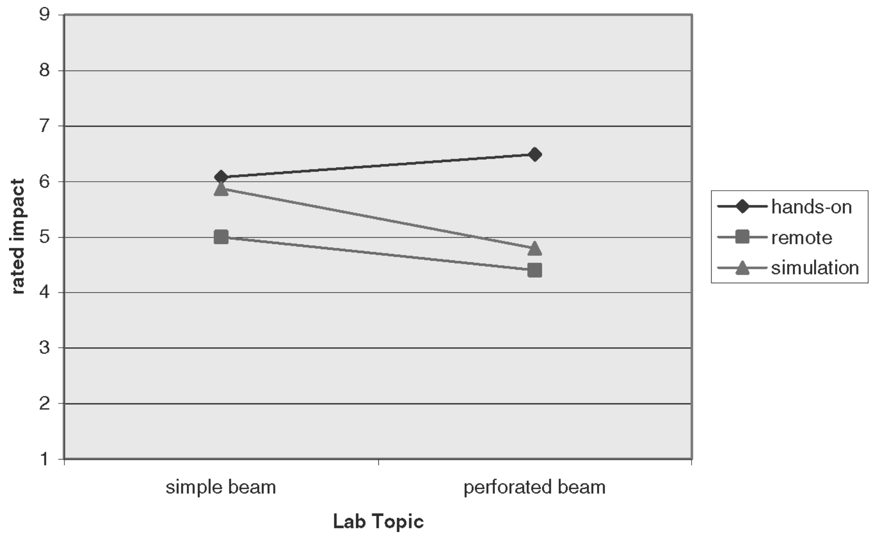

Fig. 6. Mean student ratings of the educational impact of specific labs, by lab format and topic.

varied by lab group did not find large effects. For the variable *previous GPA*, the ICC due to lab group was only .04, while for the variable *SAT-Verbal* it was .08.

5.2 Student Perceptions of the Educational Effectiveness of Lab Activities

In spite of the aforementioned evidence that student learning outcomes (measured by test items specifically focused on conceptual knowledge related to lab content) with remote labs and simulations are equal or superior to hands-on labs, students' self-assessments gave a different picture.

Students rated traditional hands-on labs as higher in educational effectiveness than remote and simulated labs (see Figure 6). The graph also reveals that the rated advantage of the traditional hands-on lab over simulations and remote labs was greater for the second lab topic. This may be because for the second lab, students had actually experienced both hands-on and nontraditional formats. An alternative explanation, though, is that the more complex perforated beam experiment is difficult to fully understand without benefit of direct physical contact with the apparatus, and that this greater need for hands-on contact is reflected in the student ratings. Students were also asked to directly compare the effectiveness of the remote (or simulated) lab format versus the hands-on. Roughly half of the students (49.3%) rated the two formats as "about the same" in effectiveness, while 39.4% rated nontraditional formats as "less effective" and 11.3% as "more effective." Thus, while most students believe that nontraditional labs are roughly equivalent or even superior in effectiveness to hands-on labs, a substantial minority (nearly 40%) see them as less effective. This raises the question of whether these individual differences in lab format preferences could be predicted from individual characteristics of the students, a possibility that we investigate in the next section.

Table III. Satisfaction with Specific Aspects of the Remote and Simulated Labs

	Remote Lab		Simulation		t Test for Difference	
	Mean	Std. Dev.	Mean	Std. Dev.	t obs	d.f.
Overall satisfaction	5.55	1.91	5.64	1.94	−0.35	212
Feeling of immersion	4.93	1.92	5.24	1.87	−1.16	204
Ease of use	6.69	1.93	6.25	2.08	1.62	211
Obviousness of use	6.30	1.92	5.96	2.01	1.23	210
Total time required	7.12	1.96	6.21	2.17	3.21*	209
Convenience in scheduling	7.03	2.15	6.42	1.82	2.20*	209
Convenience in access	7.25	1.89	6.61	1.66	2.63*	209
Clarity of instructions	6.30	1.95	5.19	2.41	3.71*	211
Reliablity of software	6.83	1.95	6.30	1.98	1.97*	211
Feeling control over the exp.	5.51	2.19	5.89	2.17	−1.27	213
Sensation of reality	4.48	2.16	4.66	2.25	−0.59	212
Extend to real structures	5.38	2.09	5.76	2.00	−1.38	210

* = $p < .05$.

Another, more detailed, way to investigate student beliefs about lab effectiveness is by checking what *specific aspects* of the lab work (across both lab formats) students believed to be most useful in promoting understanding of the concepts taught in the course. The specific aspects rated were: preparatory instructions, data acquisition, preparation of the lab report, collaborative teamwork, and actual physical presence in the lab. Consistent with their overall ratings of lab effectiveness, students rated physical presence in the lab as most important (mean rating = 7.03). Interestingly, they rated teamwork as the second most important aspect (mean = 6.78), suggesting that they are well aware of the educational value of collaborative work effort. Data acquisition was rated third most important (mean = 6.57), followed by the preparatory instructions (6.26), and the lab report (5.71).

Students also rated how satisfied they were with specific aspects of the remote or simulation-based lab, depending upon which experimental condition they were in. These results are given in Table III.

The results given in the table show that remote labs were rated more highly than simulations on aspects relating to ease of use, convenience, and reliability. However, note that these are between-subjects comparisons because no student in this study experienced labs in both remote and simulation formats. It is interesting to note that there was a slight (but insignificant) advantage for simulations over remote labs on measures relating to the amount of control the student felt, the sensation of reality, and the confidence that the results would generalize to real structures. We hypothesize that these small differences, if real, might be due to the high degree of interactivity and active participation that simulation affords to students. After all, the remote lab interface used here is designed to operate in batch mode, with the student submitting requests for data acquisition "runs" and receiving the results after a (brief) time delay, while the simulation is designed to operate in real time, with the student given the ability to change camera views and move the location of sensors.

5.3 Individual Differences in Lab Preferences

The results reported previously show that students exhibit differences of opinion as to the relative efficacy of remote and simulation-based labs. It seems natural to ask whether any of these differences seem to be related to differences in student ability or cognitive style. One relevant analysis has already been reported earlier, in which overall academic ability (measured by GPA) was used as a covariate in assessing the effects of lab format. As reported before, the covariate was only marginally significant, and the pattern of significance regarding the effects of lab format did not change appreciably.

There are reasons to be especially interested in the spatial ability of students. The remote lab interface can be seen as a filter that inevitably restricts flow of information to the student compared to the traditional hands-on format. For example, the visual input in remote labs is restricted to video from a single camera focused on the apparatus. It seems obvious that students might vary in their ability (and desire) to function under this kind of restriction. In particular, we hypothesized that students with high spatial ability might be better able to visualize what is occurring with a remotely operated lab apparatus, and thus better able to learn and reason effectively about the remotely operated lab setup. Therefore, we investigated whether student spatial ability influenced either learning outcomes or rated satisfaction with aspects of remote labs and simulations. To do this, we computed a total spatial ability measure as the sum of scores on the three spatial ability subtests (paper folding, card rotation, and surface development). We then separately correlated this ability measure with both learning outcomes and the satisfaction rates for those aspects of the labs summarized in Table III for remote and simulation-based lab groups. We found no significant correlation of spatial ability with the learning outcome measure (test score). We did, however, find that for students experiencing remote labs, spatial ability was negatively correlated with overall satisfaction (Pearson $r = -.29$, $p < .05$). For students experiencing the simulation-based lab, spatial ability was (marginally) negatively correlated with a “feeling of immersion;” $r = -.26$, $p < .10$. These findings were unexpected. It seems that students with high spatial ability were somewhat less satisfied with remote labs (or simulations). One possible explanation is that students with high spatial ability want to exercise it: They can do so when in the presence of the real device. To a lesser extent, they can use their spatial ability with the simulator: They can rotate and scale the representation. But with the current interface on the remote apparatus, their options are the most limited. Another possible explanation is that highly visual students can already simulate an experiment in their mind, and therefore want to see the real thing, not a simulation or low-resolution image.

To further investigate individual differences in perception of remote- and simulation-based labs, we analyzed responses to survey items that elicited student ratings of the importance of various aspects of the labs “for your understanding of the concepts taught in the course”. The lab aspects to be rated were: *preparatory instruction, data acquisition, lab report, teamwork,* and *physical presence in lab*. Ratings were made on a 1–9 point scale, with a rating of 1 labeled as “not at all important” to 9 as “absolutely crucial.” Preliminary analyses

Table IV. Relative Student Ratings on Importance of Lab Aspects for Conceptual Understanding

Lab Aspect:	Mean rel. Rating	Std. Dev.	Mean (Cluster 1)	Mean (Cluster 2)
Preparatory instructions	.195	.045	.235	.187
Data acquisition	.204	.041	.258	.194
Lab report	.176	.046	.197	.172
Teamwork	.208	.050	.125	.223
Physical presence in lab	.218	.043	.184	.224

For total sample and by cluster ($N_1 = 32$, $N_2 = 176$).

indicated that students seemed to vary considerably in their mean ratings on this task, so *relative* ratings (i.e., divided by the sum of a student's ratings to all 5 items) were computed and analyzed. In order to investigate differences in student ratings, we ran a k-means cluster analysis on student profiles on these 5 relative ratings, specifying a 2-cluster solution. The final cluster profiles of the 2 derived groups are shown in Table IV.

Cluster 2 is dominant in terms of size (representing N = 176 students). The mean profile of ratings for that subgroup of students gives the highest ratings to "physical presence in lab" and "teamwork," indicating that these students value interaction, both physical and social. Cluster 1 students, on the other hand, give relatively high ratings to the importance of actual data acquisition and preparatory instructions. These students might be said to have a relatively narrow task focus. We checked whether membership in either group predicts learning outcome score, but found no relationship. However, students in Cluster 2 have significantly higher SAT-Math scores and (marginally) higher spatial ability scores.

5.4 Lab Group Work Patterns

The student feedback questionnaires also asked for descriptions of patterns of collaborative and noncollaborative work activities in their lab group, both for labs performed in traditional hands-on format, and in nontraditional format (either remote or simulation). We analyzed this data at the lab group level, using the most frequent response for each lab group's members for each question. The first question concerned how students in the lab group planned lab activities, the second how lab group members were involved in data acquisition, and the third the writing of the lab report. Table V shows the mean proportion of affirmative responses to each questionnaire item.

The most obvious difference in lab group work patterns between hands-on and nontraditional formats (i.e., remote labs and simulations), documented in Table V, is that students tended to more often be in one room when collecting the data for traditional labs (74% of the time, versus only 18% for nontraditional formats), and more often collected the data from different locations for nontraditional labs. While this finding does not seem surprising, it should be noted that some lab instructors directed their students to collect the data individually for remote labs and simulations, so the exact percentages of students collecting data collectively versus individually may not generalize to other instructional situations. A somewhat disturbing finding was that in the remote/simulated labs, not all students were involved in data acquisition 16% of the time (versus

Table V. Reported Relative Frequency of Lab Group Work Patterns (simulation and remote vs. hands-on labs)

Lab Group Work Pattern	non-trad. (sim/remote)	Hands-on	Difference
Preliminary planning: did not meet beforehand	0.58	0.44	0.13*
Preliminary planning: met in person	0.13	0.29	−0.16*
Preliminary planning: met by phone	0.03	0.04	−0.01
Preliminary planning: met via computer	0.14	0.14	0.00
Data acquisition: not everyone involved	0.16	0.04	0.11*
Data acquisition: all in different locations	0.49	0.13	0.36*
Data acquisition: all in one room	0.18	0.74	−0.57*
Report writing: not everyone involved	0.16	0.13	0.02
Report writing: all in different locations	0.67	0.66	0.01
Report writing: all in one room	0.11	0.14	−0.03

Differences in proportion of work patterns between the two types of lab format are also given. Asterisks indicate significant differences as determined by McNemar's test [Hays 1973].

only 4% of the time for the hands-on). The implication is that some students are "delegating" the data collection task to their classmates. While the delegation of data collection is common in scientific practice, such delegation was not intended by the course designers. This finding suggests that extra effort may be required of instructors to ensure full participation by group members in nontraditional lab formats.

Other differences in lab group work patterns were noted for the planning stage. More lab groups (58%) reported that they did not meet beforehand to plan work for the remote/simulated lab, as compared to the hands-on lab (44%). Of those groups that did work together to plan the lab, fewer reported meeting in person for the nontraditional lab (only 13%, versus 29% for the hands-on). No significant differences between lab formats were noted for patterns of lab report writing.

5.5 Student Observations

In a questionnaire, students were asked to describe both the perceived advantages and disadvantages of remote laboratories and to provide suggestions for enhancements. Regarding the disadvantages, one student wrote "you cannot get a sense of what is actually happening." This implies a lack of a sense of presence delivered by the interface. Likewise, another student said "it was very difficult to see what was going on, and what the data meant." However, this same student said that an advantage of the remote laboratory was that "it allowed each student to do the lab at his own pace and convenience."

This was a common theme throughout the responses. Students felt somewhat disconnected from the apparatus using the remote laboratories, yet liked the convenience and ability to do things at their own pace. One student said "with additional work, the remote labs could be almost as effective as a traditional lab." This and other comments implied that the students thought the technology could be improved, and had promise.

Many students observed that remote labs were "very difficult to perform as a team" and thought this was an area for improvement. The implication is that many students do in fact value the team experience of hands-on labs.

While many students had comments along the lines that remote labs “just can’t beat hands-on labs,” there was an opposite opinion: “Hands-on labs are pointless in the way you do it. It is just busy work, no one really learns anything except dreading doing an extremely drawn out lab report for a simple experiment.” In other words, for some students, hands-on labs are not valuable, perhaps because they are not challenging, or because the benefit is not worth the time expended. However, in our class observations, we noted much variation in perceived level of difficulty; some groups of students found the experiments difficult conceptually, while others found them easy and obvious.

Students observed that when running remote labs, one could not easily ask a question of a teaching assistant or instructor, and some suggested this capability as a possible enhancement to the system. They also wished for more clarity in instructions on using the interface.

Many of the comments about simulated laboratories were similar to those about remote laboratories. However, there were additional comments on the theme of the believability of simulation results. Students saw a disadvantage to simulations in that “the numbers from traditional [laboratories] are important for the simulations.” In other words, simulations are dependent on real experiments. Students also observed that “there may also be a computer programming error”. This was not the case; the nonetheless, student’s point was probably that simulation results are less believable. Students also had issues with the sense of presence delivered by the simulations, saying the simulation “doesn’t feel ‘real’, feels detached.” Again, on the subject of belief, students said “seeing is believing and [hands-on] behaviors reinforce the concepts more clearly.”

6. LIMITATIONS

A general limitation of most studies comparing different educational treatments is that, inevitably, some specific version of each treatment condition must be evaluated. For example, some other specific realizations of hands-on, remote, and simulated laboratories might differ in relative effectiveness. Our study was a relatively naturalistic comparison of the hands-on and remotely-operated laboratories currently in use at a major engineering school; the simulations used here were created specifically for this study. These simulations were designed to use some of the natural affordances of the medium (e.g., 3D rotation of the displayed apparatus), rather than simply trying to reproduce specific aspects of the other lab formats. A specific limitation of this study was the fact that the two lab topics studied, that is, stress on a solid beam and stress on a perforated beam, were highly related conceptually and educationally. This meant that in our repeated-measures design, it was more difficult to separate the educational effects of the hands-on and nontraditional lab formats experienced by each student.

7. DISCUSSION

7.1 Learning Outcomes

In this study we asked which types of labs are most effective in promoting understanding of lab topics. The learning outcome results based on a test of lab-related conceptual knowledge show that both simulations and remote labs work at least equally well as hands-on labs in promoting understanding of course concepts specifically related to the lab topic. This suggests that in courses where the lab is intended primarily to aid in conceptual understanding of the course content, remote and simulation labs can be valuable tools, and perhaps even preferable to the traditional hands-on lab.

Why did the remote and simulated labs do as well as or better than the traditional hands-on lab in promoting understanding of course concepts? There are a number of possibilities suggested by the student responses to the survey and interview questions. One is that much of the attention and time of students in traditional hands-on labs is devoted to understanding the procedures to be followed and to setting-up and taking down equipment, and consequently they focused less on developing conceptual understanding of how the data and relevant theories/concepts relate. Another possibility is based on the observation that students performing remote and simulation-based labs more often collected the data individually. Under these conditions, students presumably had more opportunity to repeat experiments, vary parameters and observe their effects, and otherwise structure their own learning. According to the principles of inquiry learning, such affordances are especially valuable in developing and assimilating knowledge. In more traditional terms, the observed advantages for remote and simulation-based labs could simply have been due to more “time on task” in the data acquisition phase. No direct measures of time spent in specific subtasks were taken in the present study, however, so this possibility remains speculative. Finally, it could be that students’ use of social and instructional resources differ in nontraditional lab formats. In order to better explore these possibilities, future research should be designed to collect detailed data on the nature of individual and group activities in each of these formats.

In this within-subjects research design, each student experienced one target lab in traditional hands-on format and one technology-enabled lab. The order in which different lab formats are experienced may have an effect. Figure 5 suggests that scores increase in the second experiment if the first was hands-on. This apparent effect is most dramatic for simulations, and could be because the affordances of the simulation were of more use on the second, more complex experiment. But it could also be that a simulation is more believable and therefore better used if it follows a hands-on experiment.

7.2 Student Preferences for Lab Formats

Remote labs and simulations are attractive in some educational settings for reasons of cost, convenience, and wider access. We asked what students thought of the different lab types. In the ratings and open-ended interviews, students gave especially high marks to the remote lab for reasons of convenience, ease of setup, and the relatively modest time required to run the lab.

Of course, these conceptual knowledge results do not bear on the issue of how well these lab formats can be used to teach instrumentation and physical laboratory techniques [ABET 2005]. Common sense suggests that if one of the goals of the lab experience is to teach such practical skills, the hands-on lab can be expected to be the best, or in fact the only feasible, alternative. Such a belief or expectation may be the reason that students rated the educational effectiveness of the traditional lab higher that of the remote lab (or simulation). In addition, many students voiced a preference for hands-on labs in the open-ended comments.

Simulations had certain unique advantages as well. Compared to remote labs, simulations got higher ratings on presence and "realism" measures. This finding is somewhat ironic because the simulation is the one lab format in which the data is simulated, not real. One obvious hypothesis to explain this finding is that the perceived realism of the exercise and the involvement of the student may be due to student *interaction* with the display in the simulation, by changing views, sensor points, etc. This finding is consistent with predictions of constructivist theories of education.

Students in the simulation lab conditions seemed relatively unhappy with the provided instructions on operating that technology, which seemed to have an unexpected serendipitous side-effect: Because the students didn't understand the instructions, they sought more help from TAs, fellow students, and instructors. Paradoxically, this extra help may have contributed to the relative success of the simulation format in achieving good learning outcomes. In other words, bad instructions seemed to force increased commitment to social sense-making activity, which in turn resulted in better learning. This "floundering" phenomenon might be studied in future research by varying both the quality of instruction and availability of human help. This also has implications for distance learning applications; it may be helpful for students to be in the same time zone; if not, it may be important for them to have an asynchronous way of communicating, such as email or electronic message boards, not only to gain access to help, but also to discuss the experiments after they have been done.

7.3 Differences in Work Patterns in Different Lab Formats

In the technology-enabled lab formats, the students usually ran the labs individually. This is different from the hands-on situation where the students run labs together; in such situations often only one student actually interacts with the apparatus, while the others watch. If witnessing the actual physical experiment is the important thing, we would expect hands-on labs to result in better learning outcomes. However, if individual interaction and the potential for multiple runs of the procedure are more important, then both simulations and remote laboratories may have an advantage. This could account for the learning outcomes observed here for remote and simulated labs.

We cannot claim that this is the reason that simulations and laboratories produced equal or better learning outcomes. However, we think this is a plausible conjecture in line with constructivist theories of education, and might be tested in future research in the following way: the level of interactivity in the different lab activities might be varied. For example, remote labs might be built which allow for more variation and immediate feedback from the experiment. Symmetrically, we might vary the amount of interactivity in the hands-on situation; perhaps making sure that all students actually manipulate and control the apparatus might produce different outcomes than the situation common to hands-on lab experiences, in which one student runs the apparatus and the others watch.

It may be that most of the learning for a lab experience takes place after the actual lab session, when results are compiled, analyzed, and discussed, and that students understand this. This topic deserves further study because in distance learning situations students may not be able to meet in person. To compensate, other technologies might be introduced into nontraditional environments. Solutions ranging from instant messaging to electronic whiteboarding might increase team learning: This is a topic for future research. The report writing part of the lab experience would have to be done either individually, or mediated through some form of electronic coordination technology. We might reasonably predict that face-to-face meetings will be preferable. However, it is possible that students forced to write up their individual lab results may actually learn more, depending on their ability to work through conceptual problems. Theories of cooperative learning (e.g., Slavin [1996]) suggest that the group process of discussing and deciding on conclusions is indeed a highly beneficial educational activity. Our overall pattern of results suggests that although most students feel group work aided their understanding, a combination of individual and group work may be optimal. For example, the interactive, hands-on experience of individual experimentation followed by group discussion of the results might be better than all-group work, which might explain the relative success found here for the remote lab format. It may be that such a mix of solo and group work is more important than the specific technology platform used.

7.4 Individual Differences in Relation to the Lab Formats

We also investigated the relationship between student characteristics and learning effects. We found no significant correlations; whether a student learns from a particular lab type appears to be independent of previous grades, SAT scores, or spatial ability. While this may not be surprising, it is nonetheless reassuring; the new lab types are not worse for students of either greater or lesser motivation or ability. We also did not find lab instructor or section effects on learning. We did find some tendency for high-spatial ability participants to prefer hands-on labs.

We noted that there were some individual and subgroup differences in terms of beliefs about the educational effectiveness of specific lab activities. The students clustered into one large group focused on learning outcomes and lab group process, while those of a smaller group focused more on data acquisition and were concerned with the clarity of instructional material related to the technology of the labs. This finding echoes previous research showing that students can vary in their specific educational goals and beliefs about learning. For example, Heyman and Dweck [1992] found that students can be characterized as adopting either “learning goals” or “performance goals,” and that those with the former tend to have better educational outcomes.

8. CONCLUSIONS

Our results indicate that remote and simulated labs can be at least as effective as traditional hands-on labs in teaching specific course concepts. Students do express preference for traditional hands-on labs, but learn the relevant concepts as well or better with the newer forms of laboratories.

Our secondary focus was on how lab groups functioned. We found that the introduction of new technologies can result in differing patterns of coordination and communication between students. Newer technologies led to more solo interactions with apparatus in the data acquisition phase. A constructivist perspective would suggest that individual students may better construct and retain knowledge as a result of the interactive control they exert over the data acquisition apparatus in remote and simulation-based labs. By contract, in a traditional hands-on lab, some students may take a passive role in organizing activities and collecting data. Conversely, lab teammates in remote and simulation conditions still communicated with each other to discuss the lab results and write the reports, perhaps preserving the cooperative learning advantages of the traditional lab team.

Taking a situated cognition perspective, we believe that these new patterns of coordination and collaboration activity may be a byproduct not just of the technology itself, but also of the course context (including social communications and work patterns) in which it is implemented. One implication of the present results, supported by the conclusions of Sonnenwald et al. [2003], is that future evaluations of new lab technologies should take into account these new collaborative work patterns because we believe that they are a critical contributing factor to the positive learning outcomes found here.

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