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Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories

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ABSTRACT

A large-scale, multi-year, randomized study compared learning activities and outcomes for hands-on, remotely-operated, and simulation-based educational laboratories in an undergraduate engineering course. Students ($N = 458$) worked in small-group lab teams to perform two experiments involving stress on a cantilever beam. Each team conducted the experiments in one of three lab formats (hands-on, remotely-operated, or simulation-based), collecting data either individually or as a team. Lab format and data-collection mode showed an interaction, such that for the hands-on lab format learning outcomes were higher when the lab team collected data sets working as a group rather than individually collecting data sets to be combined later, while for remotely-operated labs individual data collection was best. The pattern of time spent on various lab-related activities suggests that working with real instead of simulated data may induce higher levels of motivation. The results also suggest that learning with computer-mediated technologies can be improved by careful design and coordination of group and individual activities.

1. Introduction

1.1. Overview

The laboratory is where elegant scientific theories meet messy everyday reality. This observation helps explain why laboratory experiences are at the core of undergraduate education in science and engineering. The data that is obtained from a lab assignment (and the procedures used to obtain that data) vividly and memorably demonstrate both the power and the limitations of these theories. The power of theories stems from their ability to predict actions and behaviors in the real world, and their limitations stem from the simplifications involved in these predictions. For example, while a textbook exercise might instruct the student to "ignore the effects of friction" in calculating forces and accelerations, data obtained in a lab is affected by such "nuisance" factors, bringing home the point that that the equations relating force, mass, and acceleration only approximate the behavior of real objects in a real environment.

Yet it seems inevitable that laboratory experiences in science education will have to change as technology and economic trends transform educational institutions and curricula. For educational institutions, the economic incentives to use new technologies are obvious. Use of new technologies lessens the costs associated with classroom and laboratory space. For students, new technologies can be convenient, eliminating the need to physically attend a class. But many educators doubt that crucial educational experiences can be effectively delivered through technology (Magin & Kanapathipillai, 2000). A crucial issue in designing distance-learning offerings in the sciences has been that scientific practice in the form of experimentation is widely agreed to be an essential component of science and engineering disciplines. Laboratory-based experiences are key to acquiring necessary skills in these disciplines, and these experiences can help reinforce and deepen conceptual understanding of content. But laboratory-based experiences are often assumed to require physical presence. Can these critical experiences be effectively delivered at a distance, or by computer simulation? This is the pragmatic issue we address here.

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Researchers in the field of information systems have noted with alarm the lack of systematic studies of technology's effects on educational learning outcomes (Alavi & Leidner, 2001; Alavi, Marakas, & Yoo, 2002; Ma & Nickerson, 2006). In order to fully understand the effects of introducing new technologies into education in the sciences, particularly into science laboratory experiences, carefully designed (and large-sample) evaluation studies are needed. To be maximally useful, these studies should examine a range of behavioral, attitudinal, and outcome measures, and be designed taking into account the educational objectives of educational laboratories.

Doubts and prejudices about the possibility of designing effective distance-learning experiences with science laboratories may be exacerbated by a lack of agreement about what educational laboratories are designed to teach, because there are many possible educational objectives that a course-related laboratory might be designed to achieve. For example, in 1997 the American Association of Physics Teachers described five important goals or skills to be improved by educational physics laboratories: 1) Designing experiments; 2) Experimental and analytical skills; 3) Conceptual learning; 4) Understanding the basis of knowledge in science (direct observation vs. inferences based on theory); 5) Developing collaborative learning skills. The Accreditation Board for Engineering and Technology (ABET) in 2005 listed a range of possible goals for education laboratories in engineering, from the very general to the very specific. At the most general end of the spectrum is the goal of increasing students' understanding of the nature of science and scientific experimentation. Goals on the specific end of the spectrum include introducing students to particular lab techniques and familiarizing them with commonly used laboratory equipment and tools. These highly specific goals may be the most difficult to achieve with remote or virtual laboratories. Three goals listed by ABET that are intermediate in generality, are: 1) teaching the design of experiments, 2) illustrating scientific concepts and principles introduced in the course, and 3) teaching social and team work skills. In the present paper we ignore the first of these (design skills), because it is our belief, backed up by surveys of the literature (e.g., Ma & Nickerson, 2006), that student laboratory experiences are usually meant to deepen the understanding and application of course material and are only rarely intended to teach experimental design skills (cf. Chen, 2010). Therefore, we focus on the second and third goals: promoting learning of course concepts and teaching social and team work skills with laboratory experiences. In particular, we investigate if these aspects of educational laboratories are intertwined.

Because science labs have traditionally been performed by students working in lab teams, it seems important to ask if teamwork skills and lab team work patterns are associated with learning outcomes for technology-enabled educational science laboratories. That lab teams are the norm in educational science labs is probably not an accident. First, there is the practical benefit that using lab teams means that a fixed number of experimental setups can serve a greater number of students. Second, a great deal of research in education over the past 20 years has established that cooperative learning is remarkably effective, especially in technical and scientific fields (e.g., Colbeck, Campbell, & Bjorklund, 2000; Johnson & Johnson, 2009; Slavin, 1983; Springer, Stanne, & Donovan, 1999). The benefits of cooperative learning appear to extend to online learning environments (e.g., Huang, Hwang, & Yang, 2010; Krause, Robin Stark, & Mandl, 2007; Looi, Chen, & Ng, 2010; Lou, Abrami, & d'Apollonia, 2001). Third, it has been argued by those adopting a constructivist approach to science pedagogy that knowledge is not only situated in a physical context, it is socially constructed (e.g., Pea, 1993; Gagnon & Collay, 2006; Hannafin & Land, 1997; Hofstein & Lunetta, 2004). Thus, a full understanding of how new technologies might affect learning and motivational outcomes from educational laboratory experiences will require looking at patterns of social collaboration in the lab group (e.g., Janssen, Kirschner, Erkens, Kirschner, & Paas, 2010; Jermann & Dillenbourg, 2008; Macdonald, 2003).

To summarize, the present study investigates the effectiveness of traditional and technology-mediated lab practices with regard to individual learning outcomes, and investigates if any such effects of the new technologies on learning might be mediated by the effects of individual and lab team work patterns. Specifically, we compare traditional hands-on student lab experiences to two new technology-mediated forms of laboratory experience that are becoming more and more widespread in educational institutions: remotely-operated laboratories and simulations. Remotely-operated educational labs ("remote labs") offer students the ability to collect data from a real physical laboratory setup from remote locations (e.g., a dorm room, or even another city) via web-based computer technology. Computer-based simulations of educational experiments offer another means of gathering data to illustrate course concepts and principles, but using data generated by a simulation model. Both of these technological innovations have their unique benefits, including lower operational costs and convenience. However, they also have their unique limitations, including questions about educational effectiveness and student motivation. Thus, systematic and thorough evaluations of these new technologically-enabled lab formats are needed before their applicability and value can be understood and enhanced.

1.2. Previous research on remotely-operated and simulated labs in education

1.2.1. Context

Simulated or virtual labs and remote labs are often justified with economic reasons: using these new forms of labs frees up space in universities, and within a course the new lab formats reduce lab set-up and tear-down time (Magin & Reizes, 1990; Scanlon, Colwell, Cooper, & Paolo, 2004). The economic arguments may overshadow the more important question of just how effective the new lab formats are. In addition, the creation of labs implemented using these alternate technologies is often accomplished by engineers and programmers who seek to build something novel, interesting and useful. The educational effectiveness of the labs may be taken for granted, or assessed only through student course evaluations.

For whatever reasons, learning outcomes with these technology-mediated lab formats have only rarely been assessed: a review of 100 papers on virtual labs (Amigud, Archer, Smith, Syzmanski & Servatius, 2002) found the vast majority made no attempt to evaluate student performance. Another more recent review (Ma & Nickerson, 2006) found that the few studies which have evaluated learning outcomes have usually used only small numbers of students. There are good reasons why this is so: the urge to build the apparatus may not coincide with the large class sizes that permit big studies and the people who build labs do not always have the inclination or experience to assess educational outcomes. We will focus on the empirical studies that do exist, considering first the literature on simulations, and then that on remote laboratories.

1.2.2. Simulations

Simulation-based labs have been applied in different disciplines. Only a few studies so far have examined learning outcomes. Several investigations have concluded that the disadvantages of simulations outweigh the advantages. In one study of simulations in mechanical engineering education (Canizares & Faur, 1997), student ratings of simulation effectiveness indicated a resistance to simulation-based learning techniques; in another study Roth, Woszcyna, and Smith (1996) concluded that the benefits from simulations did not fully compensate for the costs associated with learning the computer tools. Lindsay and Good (2005) found that students assigned to simulations showed worse performance on certain specific aspects of knowledge (identification of assumptions, and understanding limitations of accuracy), but comparable learning on other specific knowledge components.

However, the majority of comparative studies have concluded that simulation is a good substitute for hands-on labs in teaching course concepts and their application. For example, McAteer et al. (1996) compared two simulation packages with hands-on experiments in an Animal Physiology course, and concluded that simulated labs can help students achieve a better understanding than traditional labs. The study considered time-on-task, the students' responses to course-related questions and the self-rating of their attitudes towards different labs. Another study of a pump laboratory also reported that simulation is at least as good as hands-on, as measured by students' self-assessment of their gains in technical knowledge and practical ability (Edward, 1996). Web-based virtual science labs appear to be effective even with elementary school students (Sun, Lin, & Yu, 2008).

In addition, some researchers have proposed that simulation might be most effective when it is integrated as a complementary part of a course involving hands-on labs (Abdulwahed & Nagy, 2011; Parush, Hamm, & Stubb, 2002). In a two-year evaluation of the results of using simulation in an introductory physics course, Staden, Brown and Tonder (1987) used an animated pendulum in the tutorial mainly in order to prepare for the real experiment. They argued that hands-on experiments can not be replaced by simulations, especially at the introductory level when the basic skills of investigation are very important. Dobson, Hill, and Turner (1995) used simulations to supplement conventional labs in a mechanical engineering course.

1.2.3. Possible mediating factors on the effectiveness of simulations

A review of simulation-based discovery learning summarized factors that can hinder the efficiency and effectiveness of simulations (de Jong & van Joolingen, 1998). Specifically, it has been argued that the design of the simulation is responsible for the learning differences (Russell, Lucas, & McRobbie, 2004). For example, simulations with multiple representations can produce better learning than simulation using a single representation (van der Meij & de Jong, 2006).

Social processes are an aspect of mediated communication in collaborative activities (cf. Carroll, Rosson, Convertino, & Ganoe, 2006), and may play a role in determining the effectiveness of various lab technologies. Based on examination of the communication patterns in lab-based courses, some researchers have suggested that science learning from simulations depends on peer collaboration as well as student-to-instructor discussion (Chou & Min, 2009; Edleson, Gordon, & Pea, 1999; Pea, 2004). These studies concluded that, with well-designed group processes, simulations can be the catalysts for effective learning. These results are in contrast to the more negative evaluations of simulations mentioned above (e.g., Canizares & Faur, 1997). This line of thinking suggests that resistance to simulations can be overcome through group processes, and that strong peer-to-peer interactions, as well as instructor interactions, can help to produce better results with the new lab types. In other words, the scaffolding around the lab may be at least as important as the lab itself.

Other mediating factors may play a role in determining the effectiveness of various lab technologies. It has been argued that the variation of time on task in different labs should be considered when comparing learning outcomes (Stein, Nachmias, & Friedler, 1990). Also, the evaluations given to simulated labs are found to be contingent on the design of computer systems (Russell et al., 2004), learner's attitudes, prior instruction, and instructors (Marshall & Young, 2006).

1.2.4. Remote laboratories

Remote laboratories were introduced as an alternative to both simulated and hands-on experiments. They are computer-mediated, and can be performed from anywhere, as with simulations. But in a remote lab the student is controlling an actual physical apparatus, and obtains real data from a physical experiment, the same type of experiment that would be run in a hands-on lab. The development of remote experimentation has grown rapidly, with hundreds of implementations now in existence around the world (e. g., Alamo et al., 2003; Hanson et al., 2009; Kong, Yeung, & Wu, 2009; Saliah-Hassane, Burnett, & Loizeau, 2001; Shen et al., 1999; Ogot, Elliot, & Glumac, 2003; Potter et al., 2001).

1.2.5. Possible mediating factors on the effectiveness of remote labs

Olson and Olson (2000) suggested that it is not just the nature of the technology that determines the effectiveness of distance work, but also other factors such as the strength of ties between group members. Sonnenwald, Whitton, and Maglaughlin (2003) also examined group processes in remote laboratories. They showed that final learning outcomes were comparable between different labs types; but this may be true only because students seemed to engage in behavior which compensates for the shortcomings of the newer technologies (c.f. Lindsay, Naidu, & Good, 2007; Mayer, 2001). This idea suggests that in studying lab effectiveness we need to pay close attention to students' learning-related behaviors, including both individual and group processes.

One previous project to develop remote laboratories for mechanical engineering courses has been described by Esche, Chassapis, Nazalewicz, and Hromin (2002). In subsequent papers, a theoretical framework was proposed that identifies some factors that the literature suggests may influence lab learning outcomes (Nickerson, Corter, Esche, & Chassapis, 2007), and an evaluation study was described (Corter et al., 2007). The measured student learning outcomes from the evaluation study demonstrated that simulated and remote labs can work at least as effectively as hands-on labs in promoting conceptual understanding, yet an affective rating instrument showed that most students express a general preference for the hands-on labs.

Specifically, the results of Corter et al. (2007) show that remote labs were slightly more effective in terms of promoting understanding of basic course concepts. In that study students performed two experiments, the first being a simple beam bending experiment, and the second being a more complex beam bending experiment with a perforation. Each student experienced two different lab types: for example, the student might have used remote technology for the first experiment and hands-on for the second. Remote and simulated labs had an advantage in learning outcomes on the first simple beam experiment, but not for the second, more complex beam experiment.

Corter et al. (2007) also found that the specific student lab groups contributed a large variance component to knowledge test scores. This observation raises the question: What is it about a lab group that is highly associated with learning effectiveness? One possible explanation is suggested by the additional observation that different lab groups exhibited different patterns of collaboration. Therefore, in the current study we collected detailed information on lab group work patterns, and also directly manipulated one simple aspect of collaboration: whether the groups collected their data sets working as a group, or whether each individual student collected a separate data set before writing the lab report as a group.

In summary, previous evaluations of remotely-operated laboratories and laboratory simulations in the literature have tended to focus on describing the application and reporting student and instructor evaluations of the new applications. Only a few studies have compared learning outcomes for remote and hands-on labs (e.g., Corter, Nickerson, Esche, & Chassapis, 2004, 2007; Lindsay & Good, 2005; Sicker, Lookabaugh, Santos, & Barnes, 2005; Sonnenwald et al., 2003). The general conclusion from these studies is that learning outcomes are roughly equivalent no matter which format of lab is used: traditional hands-on labs, remote labs, or simulations. In general, students prefer traditional hands-on labs, but rate the remote labs highly on convenience and ease of use. Finally, students show different patterns of work and collaboration, both between lab groups and between lab formats. These process differences seem to be associated with differences in learning outcomes. The next section examines this issue in more detail.

1.2.6. Connections between learning outcomes and group process in educational labs

Assessing the effectiveness of hands-on, remote, and simulated labs is not as simple as applying different levels of input to a device and measuring the resulting outputs. Educational laboratories are a microcosm of the educational enterprise, and may be designed with more than one educational goal in mind. For example, the goal of using labs to illustrate concepts and principles taught in the course to deepen student understanding deserves closer examination. Experienced writers and teachers know that any abstract concept is more easily appreciated and understood via a few well-chosen examples, and a well-chosen lab assignment can provide such an example for important course concepts. But recent theories from education (cooperative learning and constructivism) and from cognitive science (on the situated and socially constructed nature of cognition) provide formal justifications for traditional lab practices, as well as a scientific framework to investigate questions related to mechanisms by which such learning occurs.

Specifically, the importance of engagement with a physical and educational context posited by some versions of constructivist theory suggest that science learning is facilitated by direct student involvement in and increased control of investigations (e.g., Applefield, Huber, & Moallem, 2000; Gagnon & Collay, 2006; Hannafin & Land, 1997; Huang et al., 2010). According to this view, students need individual interactions with scientific equipment, so that they can explore, situate, and better remember the concepts that have been learned through lectures or demonstrations. This line of thought argues for individual data collection being the norm in laboratory exercises. One previous study (Corter et al., 2007) showed an advantage for remote and simulated labs for certain lab topics, and documented that students more often collected data individually in these conditions when the collaboration strategy was left up to the individual lab teams. Thus, the remote labs advantage observed in that study might have been due to the fact that students were more likely to work individually to collect data with remote and simulated labs, and working individually entailed more direct and active involvement in the data collection process, leading to enhanced understanding and memory.

But many constructivists also acknowledge the importance of the social context on effective student construction of knowledge (Gagnon & Collay, 2006; Hannafin & Land, 1997; Hull & Saxon, 2009; Pea, 2004). Consistent with this stance, traditional hands-on educational laboratories have often been organized around student work teams. Furthermore, the literature on cooperative learning suggests that group collaboration and discussion often leads to better conceptual understanding on the part of students compared to individual activity, with perhaps the most extensive evidence coming from meta-analytic studies (e.g., Johnson & Johnson, 2009; Springer et al., 1987; Lou, Abrami, d'Apollonia, & , 2001).

The few empirical studies comparing learning outcomes as a result of group collaboration in science laboratories reach conflicting conclusions. Smith and Hinckley (1991) found that students working in cooperative groups had significantly higher achievement than individuals. But Okebukola (1984) found no difference in the performance of groups and individuals, based on the overall pattern of pretest and posttest scores, in comparing the relative effectiveness of cooperative, competitive and individualistic situations in promoting learning in biology labs. Magin (1982) argued that individual activities and group activities are closely interconnected in collaborative situations; in his study of engineering labs, students' performance on individual exercises had a moderating effect on the effectiveness of their group collaboration. Krause, Stark and Mandl (2007) found that cooperative online groups did better on the learning exercises, but participants of the groups did not show better learning outcomes than individual learners.

These opposing arguments and ambiguous conclusions about the benefits of collaboration in science labs lead to uncertainty in theoretical predictions for our experiment. Furthermore, principles of constructivism and of cooperative learning seem to yield different predictions as to the best way to organize a lab team's data collection activities: a constructivist approach assuming that benefits arise from each individual experiencing the physical contexts of learning would suggest that individuals interacting with the lab apparatus or control interface is best, while principles of collaborative learning suggest that shared responsibility for group tasks (e.g., group data collection) may improve team cohesion and thereby facilitate others benefits of cooperative learning, such as joint meaning-making.

1.3. Goals of the present paper

The above review of the literature suggests that remote laboratories and simulations can be used as effective replacements for hands-on labs to promote understanding and learning of course concepts. But the results of Corter et al. (2007) suggest that the three types of labs are not equivalent on all measures: conceptual learning outcomes are roughly equivalent in the traditional hands-on and technology-mediated laboratories, but regarding satisfaction, students often commend the convenience of remote labs and yet express a preference for hands-on laboratories. Corter et al. also suggested that students may collaborate differently in remote labs, simulations, and traditional hands-on labs, and that these differences in social process and work patterns may affect cognition and learning, thus playing a role in determining the effectiveness of learning for the different lab formats.

Thus, the goals of the present study are to evaluate the educational effectiveness (broadly construed) of remote labs and simulations relative to hands-on labs. Our consideration of educational effectiveness includes learning outcomes, student ratings of satisfaction, effectiveness, and convenience, and lab team work patterns across different lab formats. In particular, we investigate if these differences in lab team work patterns are related to learning outcomes.

2. Experimental study

The present study was conducted at an independent college of engineering in the U.S. during the Fall 2006 and Fall 2007 semesters in a sophomore-level undergraduate course on engineering design. This course is a large lecture course taught by a single lecturer, but with multiple laboratory sections, each guided by an instructor. Some of the instructors taught only a single lab section, while others taught more than one. Within each laboratory section, the students work in laboratory teams consisting of 3–4 members each. The $N = 458$ students enrolled in the course were allowed to self-affiliate in forming these laboratory teams.

The experiment comparing the effects of lab format was implemented over the course of two successive lab sessions within the course. These two sessions (each 1 h and 50 min long) involved two laboratory experiments concerned with stress measurements on classical cantilever beam setups, one with a hole and one without. Such experimental setups are typically used in undergraduate engineering programs to demonstrate basic mechanical concepts such as the deformation of elastic bodies under loading, the corresponding strain and stress distributions in those bodies and the effect of local stress raisers on these distributions.

2.1. Method

2.1.1. Variables

The primary factor of interest in our study was lab delivery medium or format. The two beam experiments were carried out in one of three different delivery formats: as traditional “hands-on” labs (with the students physically present in the laboratory and manually interacting with the equipment), remotely operated labs (with the students accessing the equipment over a computer network via a graphical user interface), and as computer simulations (with the students performing computer-based simulations of the experimental procedure). The other factor manipulated involved the specific mix of joint and individual activities by the team members; this factor was termed “data collection mode”. In the “group” data collection mode, the lab team was instructed to work together to collect three sets of stress measurements under three different parameter settings. In the “individual” data collection mode, each student in the lab group was to collect one set of stress measurements under one parameter setting (working individually). In both data-collection conditions the lab team then decided as a group which of the three data sets to analyze.

Learning outcomes were measured primarily by a knowledge test with eight questions in total. In this knowledge test, four questions related to each of the two experiments. An example item is:

3. The strain distribution along a uniform cantilever beam with a perpendicular load applied at the free end is

a) constant
b) linear
c) quadratic
d) exponential

Also, a questionnaire was administered in the second relevant lab session to collect individual students’ opinions and relevant information about the behavior and work patterns of lab teams and team members. This questionnaire had 34 items, including questions dealing with how the lab group team was formed and its effectiveness, ratings of lab effectiveness and satisfaction, individual learning styles, and other educational resources used. Here, we analyze the questions dealing with perceived and actual learning effectiveness and important process variables such as “time on task” for various subtasks.

The laboratory format was manipulated between subjects. In the Fall 2006 semester ($N = 247$), for each beam lab the different lab formats (hands-on, remote, and simulation) were randomly assigned to the lab instructors of the various lab sections. Except for one instructor who taught three sections, a single laboratory format was assigned to all the sections taught by a single instructor, in order to minimize the difficulty of participation for instructors. In the Fall 2007 semester ($N = 211$) the three lab formats were assigned to instructors so as to minimize confounding of instructor with lab format and data collection methods. Specifically, this meant that efforts were made to assign each instructor a lab format and data collection method that the instructor had not used in Fall 2006, while keeping those two factors roughly orthogonal. Table 1 shows the complete assignment of conditions to lab sections and instructors across both years of the study.

In all three lab formats the students received equivalent instructions as to the purpose and theoretical relevance of the labs, with small differences among the conditions only in the specific instructions for carrying out the experimental procedures. The general instructions used to manipulate the data collection method were as follows. For both of these data collection conditions, each lab group team was instructed to collect three sets of data with specified parameter values that varied slightly across the three data sets. In the *individual* data collection condition students were instructed that each individual member of the lab team should collect a data set with one of the assigned sets of parameter values. To do this, they could either take turns on a single apparatus/workstation, or work simultaneously on the data collection at different workstations (for the remote and simulation formats). In the *group* data collection condition students were instructed to collect the three data sets working together (no more specific instructions were given). In both conditions, the team then picked a single data set to use in the (group) data analysis and lab report writing.

2.1.2. Instructional procedure

In each of the two successive lab sessions, each lab team performed both beam labs in the same format (either hands-on, remote, or simulation) and with the same data collection instructions. Before the lab class started, all instructors received a document explaining the experiment design and specific instructions for their section(s). These instructions regarding data-collection methods were also conveyed to the students. For each lab section, the instructor gave a 30-min lecture before the lab started, explaining the educational purpose of the lab and including a verbal summary of the data-collection methods, then a graduate student was available to answer any student questions.

Table 1
Assignment of experimental conditions to lab sections and instructors, with number of students (N) for each section.

Year	Lab Format	Data Coll.	Section	Instructor	N
1	HO	Group	1B	5	15
1	HO	Indiv	1C	5	27
1	HO	Indiv	1E	5	18
1	Rem	Group	1H	1	26
1	Rem	Indiv	1F	4	27
1	Rem	Indiv	1G	4	24
1	Sim	Group	1A	3	27
1	Sim	Group	1J	2	28
1	Sim	Indiv	1D	2	27
1	Sim	Indiv	1K	3	27
2	HO	Group	2C	4	25
2	HO	Group	2D	4	21
2	HO	Indiv	2H	1	15
2	Rem	Group	2A	6	26
2	Rem	Group	2J	3	23
2	Rem	Indiv	2I	5	24
2	Rem	Indiv	2B	5	19
2	Sim	Indiv	2E	5	16
2	Sim	Group	2F	4	24
2	Sim	Group	2G	4	18

Additional instructional support was also available. Files describing the theory, procedure and homework of the labs were posted online and distributed in the class. The theory and homework explanations were the same for the three lab formats, but the procedure file was different. Additionally, for the hands-on lab sections step-by-step instructions were given on how to set up the apparatus and collect the data. For the remote labs, the instructions given in the procedures file were supplemented by a demonstration of how to operate the remote apparatus, performed by a graduate student. For the simulated labs, the needed software was provided on a CD and was also available online. The procedure to install the software was described in a separate file and a graduate student led the class step-by-step through the procedure. After the installation, the graduate student briefly demonstrated how to use the simulation software.

The study spanned two weeks of the course. In the first week, the beam experiments (beam without a perforation and beam with a perforation) were performed during the class. A follow-up knowledge test and the questionnaire were distributed in the second week at the beginning of the laboratory class session. It took approximately 30 min for the students to finish the test and the questionnaire. Students' perceptions of the labs, their lab group work activities and learning styles were assessed by the questionnaire. The conceptual knowledge test with eight multiple-choice items was used to measure the educational effectiveness of the lab. GPA and SAT scores of individual students were obtained for use as possible covariates. Complete data (the questionnaire and the knowledge test) were available for $N = 399$ students.

2.2. Results

We are primarily interested in two sets of variables: 1) learning outcomes, as measured by the follow-up test of understanding of specific lab content, and 2) individual and lab team work patterns. Here, we report analyses of how the lab formats and data collection conditions affect one key work-process variable: individual self-report estimates of time spent in various component lab activities; we also present data on how lab teams actually allocated the work of data collection. Next, we report the effects of the independent variables on actual learning outcomes, as measured by the lab-content test. Finally, we analyze student ratings of satisfaction and perceived lab effectiveness (the type of measure most often reported in previous studies of new educational technologies), and describe how these self-report measures are associated with measured learning outcomes.

2.2.1. Individual and group process

The lab questionnaire asked a number of detailed questions about patterns of individual and group work in the two labs. One important question concerned the "time on task" spent by students across the experimental conditions, because total time spent on learning-related activities has been shown to be a significant predictor of learning outcomes in many educational applications. There are two obvious factors that might lead to differences in time on task for the various experimental conditions in the present study. First, differences among the conditions in time spent in data collection are most easily attributed to inherent aspects of the lab format or data collection mode. Second, it is reasonable to speculate that the lab formats may lead to different levels of motivation, leading to more or less effort being expended by students in various conditions, particularly in data analysis and lab report writing.

Fig. 1 shows the amount of time spent on various component lab activities by lab format. The amount of time spent on the first two component activities, receiving instructions and data collection, can be attributed mainly to the instructional content and the physical realities of the lab setup, rather than to the students' level of motivation. The remote lab condition required the least amounts of time for receiving and discussing instructions and for setup, while simulations required the most setup time (due to the required software installation step). Time spent on the next activity, data collection, is determined in part by the inherent nature of the lab delivery format and specified data collection procedures, but is also partly under control of the student lab team (and may vary with motivation), because teams and individuals are not prohibited from doing extra runs and collecting data with additional parameter settings (we explore this possibility below). Not surprisingly, students using the simulation software spent the least amount of time for data collection, while participants in the hands-on lab condition spent the most time. Finally, differences in time allocation for the remaining lab component activities (data analysis

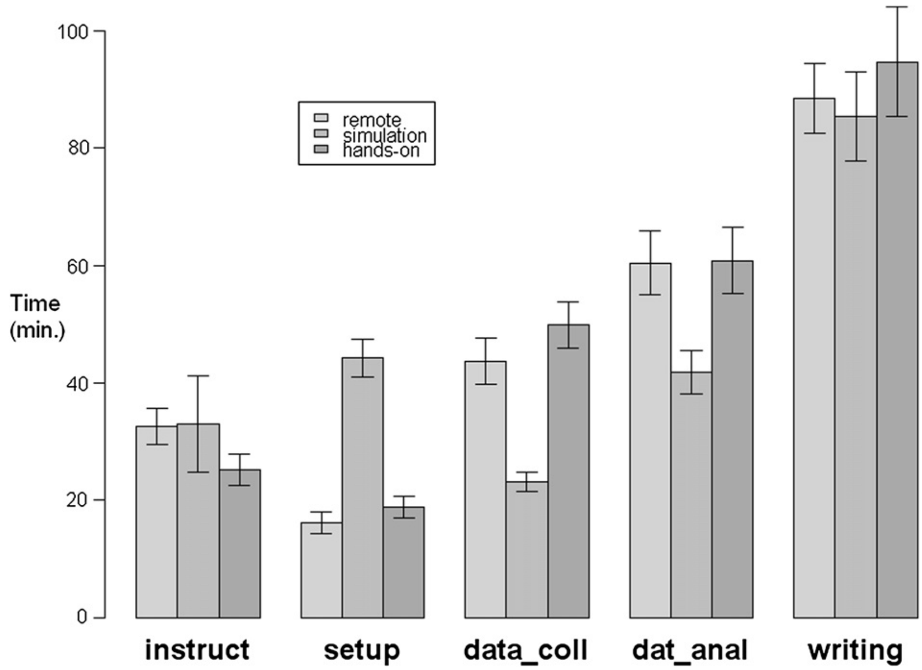

Fig. 1. Time spent on various phases of the lab activity, by lab format group. Error bars show ± 1 std. error of the mean.

and report writing) are under student control and therefore can be assumed to be affected by level of motivation. For example, students in the hands-on and remotely-operated conditions spent more time on data analysis compared to the simulation group. It could be that students in the simulation condition saw less benefit in exploring the data thoroughly because it was simulated rather than real. Hands-on students spent the most time in writing the lab report, presumably reflecting relatively high levels of motivation, though differences in time spent on this subtask were not large.

From the standpoint of constructivist educational theory, the component lab activities of data collection, data analysis, and write-up might be expected to be particularly important for promoting knowledge gains and test scores, because these activities (particularly the latter two) are assumed to involve an active search for meaning, and the relating of data to theories. The importance of time spent in these activities is confirmed by the correlations between the time spent in the various lab activities and the knowledge test scores. These correlations indicated that time spent on data collection ($r = .11$, $p = .037$) and on data analysis ($r = .16$, $p = .003$) were positively correlated with learning performance as measured by the posttest of lab-related content. The correlation between time spent on report writing and posttest score showed a positive correlation, but it was not significant ($r = .09$, $p = .111$). Correlations were negative or zero, and not significant, between learning outcomes and time spent on receiving lab instructions ($r = -.08$, $p = .118$), and time spent on experiment setup ($r = .00$, $p = .991$). A summary measure was computed, of total “work time”, defined as total time spent on data collection, data analysis, and writing the lab report. This measure of total effort differed significantly among the three lab format conditions, $F(2,348) = 6.689$, $p = .001$, $\eta^2 = .04$. Mean total work time spent on these aspects of the labs in the hands-on condition was 202.4 min (SD = 115.8), compared to 193.7 min for the remote labs (SD = 114.0) and 151.0 min in the simulation-based condition (SD = 94.8). One possible interpretation of this finding is that students are more motivated to treat data seriously when it is real rather than simulated.

Two questions on group process were included as a manipulation check for the individual versus group data collection manipulation. One item (Item 12) asked students to check one of a number of statements describing how they worked together to collect data. Two of the possible responses were “we all collected data individually, working in the same location” and “we ran the experiment together, working in the same location simultaneously”. These statements were intended as a manipulation check for the individual versus group data collection manipulation. However, the results were somewhat unexpected. Under instructions for group data collection, 94% of students in the hands-on sections, 84% of students in the remotely-operated sections, and 90% of students in the simulation sections agreed that they ran the experimental procedure as a group, as expected. However, in sections that had received instructions for individuals to collect data separately, 77% (hands-on), 20% (remote) and 38% (simulation) of students still indicated that they had collected data as a group. Psychologically, this suggests that students in the hands-on sections were more likely to judge that they were “working together”, even when they were individually collecting readings with different parameter settings. Of course, this may have arisen because in the hands-on condition, all group members must set up and share one apparatus, and tend to remain co-present during data collection even under individual data-collection instructions, while in the computer-mediated formats three separate computers were usually available.

We used an additional item in the questionnaire (Item 14; “How did your group operate the laboratory apparatus?”) to conduct a more thorough manipulation check on this factor. This analysis reveals that 83% of participants in the “individual” conditions reported that team members collected data working individually. In the “group” remote condition 85% of participants reported that that a single person operated the apparatus to collect all three data sets, while in the “group” simulation condition 63% reported this arrangement. However, in the “group” hands-on condition only 17% of participants reported designating a single person to collect data, with the more common reported procedure being that the team members took turns operating the apparatus. It may be that in the hands-on format, interacting with the lab apparatus was seen as especially beneficial educationally, or especially enjoyable, thus lab team members were careful to share

Table 2
Means and (standard deviations) of learning outcomes (total test score), by lab format condition and data collection mode.

	Lab Format:			
Data Collection:	Remote	Simulation	Hands-On	Total
Individual	4.45 (1.59)	3.97 (1.32)	4.10 (1.43)	4.21 (1.48)
Group	3.94 (1.58)	3.93 (1.72)	4.75 (1.53)	4.16 (1.66)
Total	4.23 (1.60)	3.95 (1.55)	4.45 (1.51)	4.18 (1.57)

this role. These differences in behavior among the lab format conditions should be taken into account in interpreting the superior learning outcome for the group hands-on format.

Additionally, one item in the questionnaire asked students to rate on a 9-point scale their agreement with the statement "You and your team mates worked cooperatively on this lab". Students in the hands-on sections gave the highest rating to this item ($M = 7.5$, SD = 1.37), followed by students in the simulation-based lab format ($M = 7.0$, SD = 1.91), and those using remote labs ($M = 6.6$, SD = 2.78). Students in the group data-collection conditions gave slightly higher ratings ($M = 7.1$, SD = 1.93) than those in the individual data collection conditions ($M = 6.7$, SD = 2.49). However, in a factorial ANOVA of this cooperative work pattern rating with lab type and data collection condition as between-subjects factors, only the main effect for lab type was significant, $F(2,385) = 3.251$, $p = .040$.

Another questionnaire item (#15) analyzed asked participants how many data collection runs they performed or watched in total. This figure was highest for the individual simulation condition ($M = 11.0$, SD = 11.06), presumably because individuals could try extra simulation runs quickly with little effort, and for the individual hands-on condition ($M = 14.0$, SD = 5.41), apparently because lab team members tended to gather around one lab equipment setup and watch each other collect data, even in the individual condition. For the group conditions, participants using simulations watched an average of 6.75 (SD = 5.0) data collection runs, and hands-on lab participants watched on average 5.41 (SD = 3.68) runs. This count was lowest for remote labs, where participants performed and watched only about 4.1 runs (SD = 2.7) on average, regardless of data collection condition.

2.2.2. Learning outcomes

The effectiveness (in terms of learning outcomes) of the three lab formats and the individual versus group data collection factor was evaluated by comparing total scores on the lab concepts knowledge test in a between-subjects ANOVA. In order to control for student ability in this between-subjects design, cumulative GPA prior to the current semester was used as a covariate. The unadjusted cell and marginal means are reported in Table 2, and the ANCOVA of these scores is reported in Table 3. For this analysis data from $N = 398$ students were available.

In this ANCOVA, lab format and data collection mode showed a significant interaction, $F(2,390) = 4.419$, $p = .013$, $\eta^2 = .02$, such that the hands-on labs showed a large advantage under group data collection instructions, while the remotely-operated lab format showed an advantage under individual data collection instructions. Overall, there was also a main effect of lab format, $F(2,390) = 3.197$, $p = .042$, $\eta^2 = .02$, with students experiencing the lab in hands-on format showing higher mean scores (4.45) than students experiencing the remote labs (4.23), who scored higher than students experiencing simulations (3.95). The effect of the covariate (GPA) on lab test score was positive and significant, $F(1,390) = 6.365$, $p = .012$, $\eta^2 = .02$. Fig. 2 shows the cell means, adjusted for the covariate, by lab format and data collection mode. In this figure the interaction between lab type and data collection mode can be seen clearly.

The fact that the cell with the highest mean score was the hands-on/group data collection condition is interesting, because this condition is both the traditional procedure for educational laboratories and the default procedure that had been in place in the current course for previous lab topics. Thus, it is not completely clear whether the advantage for this condition is due to educational superiority or to simple familiarity, which could have enabled the students to concentrate more on the concepts and procedures of the lab and less on understanding work-process instructions and negotiating social roles. However, it may be that the hands-on group data-collection condition creates more group cohesion and more efficient sharing of knowledge and goals, leading to better group work in subsequent data analysis and writing phases of the lab.

2.2.3. Student evaluation of labs (satisfaction)

Student perceptions of the lab's learning effectiveness were assessed by asking them to rate, using a 9-point scale, the effectiveness of the just-finished lab on three aspects: for teaching specific concepts, for increasing general knowledge of the field, and for teaching specific skills to be a better engineer. Because these three rating items were highly correlated, responses to the three items were averaged to create a single measure of student-rated learning effectiveness that yielded high reliability (Cronbach's $\alpha = .93$). Note that because these ratings were collected in a between-subjects design, students were not directly comparing lab formats or data collection modes. The hands-on labs yielded the mean highest effectiveness rating ($M = 5.28$, SD = 2.06), followed by simulations ($M = 5.06$, SD = 2.07) then remotely-operated labs ($M = 4.93$, SD = 2.20). The group data collection conditions led to mean higher effectiveness rating than the individual data collection

Table 3
ANOVA of total test scores: effects of lab format and data collection mode, controlling for GPA. Effect size estimates (η^2) also shown.

Source	SS	df	MS	F	p	η^2
Between						
GPA	15.079	1	15.079	6.365	.012	.016
Lab type	15.148	2	7.574	3.197	.042	.016
Data collection	0.472	1	0.472	0.199	.656	.001
Lab type * data collection	20.940	2	10.470	4.419	.013	.022
Error (Between)	923.954	390	2.369			

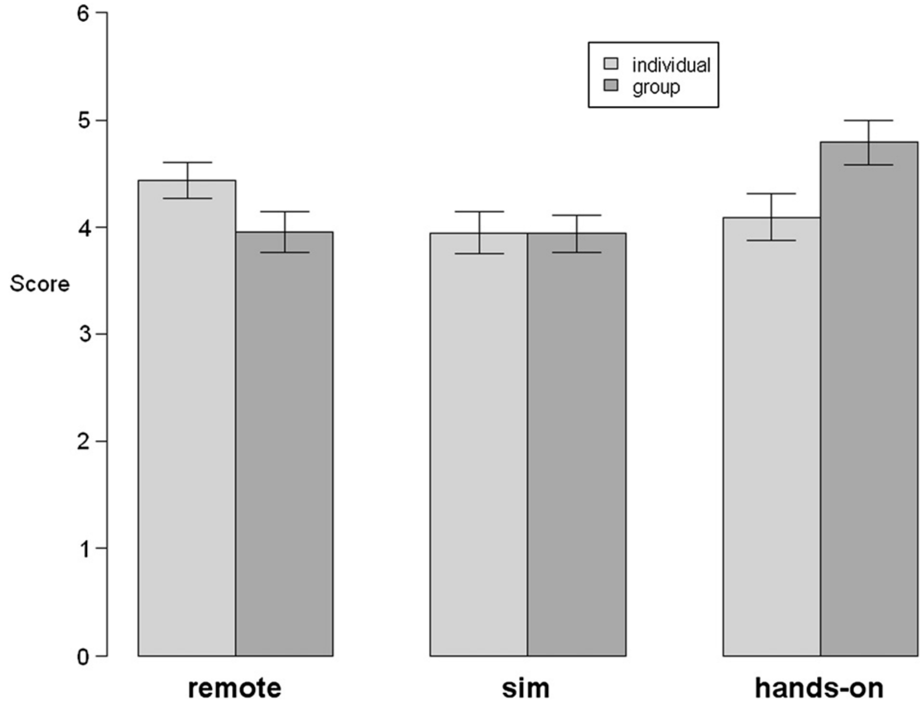

Fig. 2. Learning outcomes (total test score) by experimental condition: group means adjusted for covariate (prior grade point average). Error bars show ± 1 std. error of the mean.

conditions ($M = 5.24$, SD = 2.05, versus $M = 4.89$, SD = 2.17). However, note that the pattern of means for this student-rated effectiveness variable differs from the pattern for actual measured learning effectiveness (total test score), which was indeed highest for hands-on labs but substantially higher for remote labs than for simulations. In fact, the individual-level correlation of this composite measure of student-rated lab effectiveness with actual learning effectiveness was close to zero: $r(385) = -.05$, $p = .348$.

Table 4 presents mean scores for the student ratings of both learning effectiveness and various satisfaction measures. Several things are noteworthy about the pattern of mean ratings. First, for many of the items (including perceived effectiveness, a feeling of immersion, and overall satisfaction), hands-on labs are rated higher than simulations, which are rated higher than remote labs. This observation, along with the fact that the pattern of many of the satisfaction items show a similar profile across lab types and data collection modes, suggests a possible 'halo effect' in which a general feeling of satisfaction with the lab format determines the ratings given to specific (supposedly independent) aspects of the labs, even affecting student judgments of learning effectiveness.

A principal components analysis was conducted of the three rated effectiveness items and the eight rated satisfaction items to see if the variations in the ratings could be explained by a few underlying factors. The first two components accounted for 75% of the variance in the ratings. These components were rotated by the Varimax criterion; the rotated component loadings matrix is shown in Table 5. The first component loads on the first five items (when a cutoff of .6 is used for interpretation purposes), and can be interpreted as involving

Table 4
Knowledge test scores and student ratings (on 9-point scales) of learning effectiveness, satisfaction and immersion variables (and composites) by lab format and data collection mode.The N for each condition is shown in parentheses in the column header.

	Lab type			Data collection		Total
	Remote (147)	Simulation (148)	Hands-on (104)	Indiv. (196)	Group (203)	($N = 399$)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Knowledge test score	4.23 (1.60)	3.95 (1.55)	4.45 (1.51)	4.21 (1.48)	4.16 (1.65)	4.18 (1.57)
Effectiveness: concepts	5.01 (2.26)	5.07 (2.19)	5.25 (2.07)	4.90 (2.23)	5.28 (2.13)	5.09 (2.18)
Effectiveness: gen. knowledge	4.98 (2.32)	5.03 (2.23)	5.39 (2.12)	4.96 (2.34)	5.24 (2.13)	5.10 (2.23)
Effectiveness: skills	4.80 (2.45)	5.08 (2.31)	5.20 (2.38)	4.81 (2.42)	5.20 (2.33)	5.01 (2.38)
Average rated effectiveness	4.93 (2.20)	5.06 (2.07)	5.28 (2.06)	4.89 (2.17)	5.24 (2.05)	5.07 (2.12)
Overall satisfaction	4.66 (2.22)	4.83 (2.21)	4.96 (2.00)	4.52 (2.18)	5.07 (2.11)	4.80 (2.16)
Feeling of immersion	4.38 (2.27)	4.64 (2.23)	4.84 (1.96)	4.41 (2.21)	4.78 (2.15)	4.60 (2.18)
Ease of use	5.76 (2.31)	5.07 (2.46)	5.18 (2.27)	5.13 (2.47)	5.57 (2.25)	5.35 (2.37)
Sat. w/total time required	5.19 (2.50)	4.79 (2.54)	5.16 (2.18)	4.51 (2.49)	5.54 (2.28)	5.03 (2.44)
Convenience in scheduling	6.06 (2.31)	5.38 (2.32)	5.84 (1.93)	5.55 (2.28)	5.94 (2.18)	5.75 (2.24)
Convenience in access	6.47 (2.20)	5.56 (2.40)	6.02 (1.94)	5.79 (2.27)	6.23 (2.19)	6.02 (2.24)
Clarity of instructions	5.37 (2.46)	4.58 (2.55)	5.00 (2.42)	4.71 (2.59)	5.23 (2.40)	4.98 (2.50)
Reliability of setup	4.83 (2.88)	5.00 (2.61)	5.61 (2.44)	4.81 (2.71)	5.36 (2.65)	5.09 (2.69)
Effectiveness subscale	4.75 (2.07)	4.94 (1.99)	5.13 (1.85)	4.73 (2.03)	5.09 (1.94)	4.92 (1.99)
Convenience subscale	5.63 (1.98)	5.06 (2.11)	5.48 (1.79)	5.09 (2.06)	5.65 (1.90)	5.38 (1.99)
Immersion scale	3.87 (2.28)	4.95 (2.07)	5.59 (1.78)	4.60 (2.22)	4.83 (2.15)	4.72 (2.19)

Table 5
Component loadings for rotated solution from principal components analysis of the three student-rated learning effectiveness and the eight satisfaction items.

	Component	
Item:	1	2
Rated effectiveness: concepts	.841	.280
Rated effectiveness: general knowledge	.908	.230
Rated effectiveness: skills	.882	.191
Satisfaction: Overall	.760	.475
Satisfaction: feeling of immersion	.753	.437
Satisfaction: ease of use	.299	.804
Satisfaction: total time required	.244	.808
Satisfaction: convenience in scheduling	.164	.845
Satisfaction: convenience in access	.293	.816
Satisfaction: clarity of instruction	.432	.665
Satisfaction: reliability of setup	.511	.602

a subjective judgment of overall effectiveness of the lab. It is interesting that both the overall satisfaction item and the item tapping a feeling of "immersion" load on this component. The second component loads on the last six items, and is readily interpretable as a convenience factor.

Accordingly, two satisfaction subscales were defined by averaging the ratings for the items loading on each of these two components, and the resulting means on these subscales are shown in the last two rows of Table 4 (labeled "effectiveness subscale" and "convenience subscale"). Both subscales had excellent reliability: Cronbach's $\alpha = .94$ for perceived effectiveness and .91 for convenience. On the effectiveness subscale, hands-on labs were rated higher than simulated labs, which were rated higher than remote labs. In terms of convenience, remote labs were rated higher than both of the other two formats. One might think that simulation-based labs would be rated as very convenient, but in the present implementation the simulation software had to be installed as a first step in the lab setup. This step was not enjoyed by the students, and thus may have lowered satisfaction ratings for the simulation-based lab. It should be emphasize that the "effectiveness" subscale reflects merely a composite of the student ratings of perceived lab effectiveness, immersion, and satisfaction. In fact, it has a low negative correlation, $r(377) = -.12$, $p = .021$, with actual learning effectiveness (as measured by total lab test score).

3. Discussion

3.1. Summary

The present investigation adds to the growing literature concerning the effectiveness of new technology-enabled types of educational laboratories, specifically remotely-operated laboratories and simulations. The picture that emerges from the present results is complex, and demonstrates the many cognitive, motivational, behavioral, and social factors that might mediate the effectiveness of new instructional technologies as they are introduced into the classroom. For example, these results show that the apparent learning effectiveness of different lab delivery formats (hands-on, remotely operated, and simulation-based labs) may depend on the exact instructions given to lab teams on how to collaborate in using the technologies. Also, these data show that very different patterns of time commitment and cooperative work can arise when student lab teams perform labs in the different formats and under slightly different instructions.

Two types of evidence are provided here that the effectiveness of new lab technologies may depend largely on social and motivational factors. First, the effects of our explicit manipulation of the data collection mode showed that group data collection is more effective than individual data collection for hands-on labs, but that this effect is reversed for remotely-operated labs (in the present instantiation perhaps more naturally suited to individual experimentation). We conclude that how new technologies are used instructionally, in terms of specific requirements and activities, may largely determine their effectiveness. Second, differences in educational effectiveness among the lab types were found to be related to parallel differences in time commitment or work patterns by students. These findings underscore that comparative evaluations of these new technologies are difficult, and may be of little use unless educationally relevant variables such as student ability, time on task, and cooperative work patterns are measured and controlled.

Some comments are in order regarding the limits to generalizability of this (and many other) evaluation studies of new educational technologies. First, our measure of learning outcomes focused on acquisition and application of concepts covered in the course, and did not test for familiarity with lab equipment or procedures (although we did assess the success of lab groups in working as a team, another goal of educational science laboratories). Also, in this study we compared only a single instantiation of each laboratory format: hands-on, remotely-operated, and simulations. Therefore caution is warranted in generalizing these results to other possible realizations of each lab format. For example, the simulation software used here had to be installed by students as a first step, consequently ratings of "convenience of setup" were not high for the simulation-based lab format.

Furthermore, in this study we tried to equate not only lesson content but also *how* the labs were used: in a two-hour lab session within an actual physical laboratory setting. This highly constrained design facilitates the comparison of inherent aspects of the lab formats, but may not take advantage of all the natural affordances of the media and how they could be used. For example, it is an advantage of the remotely-operated and simulation-based labs that they could be performed asynchronously, at the times most convenient for each student team. In fact, our study's requirement that all teams run the remotely-operated labs simultaneously may have led to resource competition for control of the remote-lab apparatus, causing slight delays and thus decreasing satisfaction. But if a study were designed to take advantage of all the natural affordances of each medium, it would be difficult to ascribe causality to the medium itself, as opposed to differences in how each medium could be applied or how it tends to be used by students (i.e., at different times of day, working individually rather than working as a group, and so forth). Thus, in order to come to a complete understanding of how new media do (and might) affect educational processes and outcomes, comparing the results from both highly controlled and more naturalistic studies seems useful.

3.2. Effectiveness of lab formats – actual versus perceived

It is intriguing that students rate remotely-operated labs as less effective than simulated labs, even when the knowledge test results show an advantage in the opposite direction. Correlational analyses suggested that one possible reason is that students use a sense of immersion to judge learning effectiveness and satisfaction with the lab technology, and thus do not do a good job of rating comparative effectiveness of these technologies. Since the students here experienced only a single lab format, it is perhaps not surprising that between-subjects comparisons of their ratings do not accurately predict differences in learning effectiveness. One caveat to this result is that we measured only a single dimension of learning effectiveness in this study – how well the students learned basic course concepts. Nonetheless, if student ratings and specific learning outcomes are only weakly (or even negatively) correlated, we should be cautious in interpreting the conclusions of studies using student-rated effectiveness as the primary outcome measure.

3.3. Satisfaction with lab formats

In the present study, a preference was expressed for the hands-on labs. This is not surprising, since the hands-on format is the most immediate and vivid, and since many students (and educators) believe that educational science laboratories should teach not just application of important course concepts, but also provide experience with actual lab equipment (though proponents of remote labs might argue that more and more industrial and scientific processes are being mediated by computer interfaces). Furthermore, remote and simulated labs may allow the students to "see" or remotely operate the apparatus, but some students may need to touch and interact with the apparatus personally to understand at a deep level what is going on. This conclusion is consistent with constructivist and situated-cognition theories that stress the importance of physical context to the learning process. Thus, it is not surprising that the first factor or component underlying the ratings of satisfaction and perceived learning effectiveness has a self-rated "immersion" component. We speculate that "immersion" may also have a social component – here remote labs had the lowest ratings on immersion, as well as the highest proportion of students working individually during data collection.

On the other hand, the remote labs have a clear advantage in set-up time and convenience over the other formats, and this advantage shows up in the second component underlying the satisfaction ratings. This convenience factor may be important for students. In the present study most of the students were sophomores, and they were very busy with year-end design projects. They desire a more flexible schedule and more free time: these are the benefits that remote and simulated labs can provide but hands-on labs cannot.

3.4. Data collection mode – why is group work better for hands-on labs?

The advantage of group study in general may be explained by students' engagement in both social and task-oriented activities. Here, the definition of data collection as a joint shared task, rather than as parallel individual tasks (followed by group data analysis), had a large effect on learning outcomes for the traditional hands-on lab format. This can be seen as surprising, because instructions on how to use the data were quite comparable in the two conditions – out of the three data sets collected (in either condition) the student team was to choose one set of data to analyze and write up. It may be that the group data collection resulted in a more unified team, with everyone more likely to be satisfied with the quality of the observations. By better establishing a group identity in the data collection stage, and perhaps in jointly coordinating the lab procedure, students may tend to interact more and have a higher level of group commitment and participation in later data analysis and writing stages, which in turn leads to better performance. Also, successful collaboration requires shared mutual knowledge, and collecting data as a group jump-starts this process.

One moderating variable regarding the learning effects of data collection mode and lab format is time on task. Here, the hands-on lab sections had the highest total time on task - in particular, the Hands-On/Group condition showed the highest amount of time spent on data analysis. Again, this may be because group work increases social involvement, increasing motivation, in turn increasing time on task, resulting in better test scores. And both hands-on and remote labs led to more time being spent on data analysis than did simulations, perhaps because the data is real in the former types of labs.

3.5. Interfaces and processes – how can learning be improved?

The advantages we found in time on task and learning outcomes for hands-on labs lead us to ask: How can we design simulations and remote lab interfaces to be better? For example, simple interface changes may help. It is possible that gathering around an apparatus is more involving than gathering around a large computer screen. Consequently, a larger screen, or a screen embedded in a table top, or a screen projected onto a wall, might produce greater involvement and make collaboration easier, and thus lead to greater motivation. Our results also suggest that if educational laboratories are to be delivered in distance learning contexts it will be important to develop effective technology-related tools to promote and support remote collaboration (e.g., Jermann & Dillenbourg, 2008; Jara et al., 2009), and to expand research on factors influencing the success of online learning and scientific collaboration at a distance (e.g., Guan, Tsai, & Hwang, 2006; Kreijns, Kirschner, Jochems, & van Buuen, 2007).

Previous research on combining instructional design and support for educational laboratories may also give us some insights. It has been found that instructional support can be redeveloped to promote complex thinking in laboratories (e.g., Schauble, Glaser, Duschl, Schulze, & John, 1995; Chang, Chen, Lin, & Sung, 2008). For example, we might add multimedia explanations and graphic feedback to the experiment and thereby increase understanding (Rieber, Tseng & Tribble, 2004). Or we might provide multiple representations in the experiment, which helps when concepts are complex (van der Meij & de Jong, 2006). Group activity itself might be improved: there is evidence that the ability to collaborate effectively can be taught (Rummel & Spada, 2005).

3.6. Conclusions

While students' experiences were differently mediated by the three technologically distinct lab types, students can learn effectively with all three types. Scores on the conceptual knowledge test showed little overall difference between the lab types, and the differences in effectiveness that do exist seem largely explainable in terms of time on task (measured here by total work time), with the lab formats delivering actual data (as opposed to simulated data) resulting in both greater work time and higher learning outcomes. Total time spent in important lab activities (data collection, data analysis, and report writing) varied both across individual lab teams and across experimental conditions, and significantly predicted knowledge gains. Presumably total time spent on the lab (at least in the data analysis and writing phases) reflects degree of motivation. Highly motivated students will spend more time outside the lab analyzing and writing up their lab reports, and then will score better on the tests. In sum, social and motivational factors appear to be more important than the simple physical form of the lab apparatus and interface in determining learning effects. For example, assigning data collection as a joint team activity rather than as an individual responsibility had large effects, but interacted with the lab mode.

As far as preferences are concerned, students appear to evaluate the labs along two relatively independent dimensions: convenience and effectiveness. Attitudes toward the labs are highly influenced by the convenience dimension: students like the new lab types because they can spend less time on setup and tear-down. Unfortunately, this ease and convenience may carry over and influence student attitudes in subsequent phases of the lab; here, students in these conditions also tended to spend less time in data analysis and writing. Consequently, one challenge for instructors introducing new technology-based lab formats is to try to motivate students so that any time saved in setup is applied to the stages of analysis and writing.

Finally, our results suggest caution in using student self-reports of learning effectiveness as a proxy for the real thing: across all participants and conditions the correlation of actual test score with the student-rated average effectiveness summary score was effectively zero ($r = -.05$)! Tellingly, student-rated educational effectiveness correlated more highly with other student-rated satisfaction measures than with learning outcomes.

Our conclusion is that new technologies – remote and simulated labs - can be used effectively in science and engineering labs to teach conceptual understanding. However, group processes may differ in subtle ways for these different lab modalities. When process differences are mandated by the instructional context – such as how students are asked to collect data – these factors can interact with the effects of different lab types in affecting learning and satisfaction. These results show that development and use of new technologies in delivering educational laboratories, especially at a distance, should strive to incorporate effective collaboration tools. Consequently, the lab medium is just one factor affecting learning outcomes – the difficulty of the experiment, the process the group adopts to work together, and the amount of time the teams devote to data analysis and report writing all play a role. Thus, instead of debating the relative merits of specific laboratory technologies, future researchers may want to examine how educational goals can be achieved through the improvement of a group's collective learning process.

Appendix. Selected items from individual questionnaire for beam lab study

Lab effectiveness:

5. How effective did you think this lab was: [Circle one for each question.]
(1 = not at all effective, 9 = extremely effective)

A. in teaching specific concepts relevant to the lab topic:	1	2	3	4	5	6	7	8	9
B. in increasing your general knowledge of the field:	1	2	3	4	5	6	7	8	9
C. in giving you skills that will make you a better engineer:	1	2	3	4	5	6	7	8	9

Please indicate your agreement with the following statements: (1 = not at all, 9 = completely)

8. You and your team mates communicated effectively	1	2	3	4	5	6	7	8	9
9. You and your team mates worked cooperatively on this lab	1	2	3	4	5	6	7	8	9
10. You could depend on your team mates for help	1	2	3	4	5	6	7	8	9

Satisfaction: [Please circle one for each question]

11. Please rate your satisfaction with the following aspects of this lab: (1 = Completely dissatisfied, 9 = Extremely satisfied)

A. Overall satisfaction	1	2	3	4	5	6	7	8	9
B. Feeling of immersion	1	2	3	4	5	6	7	8	9
C. Ease of use	1	2	3	4	5	6	7	8	9
D. Total time required	1	2	3	4	5	6	7	8	9
E. Convenience in scheduling	1	2	3	4	5	6	7	8	9
F. Convenience in access	1	2	3	4	5	6	7	8	9
G. Clarity of instructions	1	2	3	4	5	6	7	8	9
H. Reliability of setup	1	2	3	4	5	6	7	8	9

Data collection:

12. Which best describes your group work pattern in running the lab/collecting data? [Check one.]
______ A. We all collected data individually, working in the same location.
______ B. We ran it individually from different locations, but more or less simultaneously, while discussing it: [Check one.]
By chat/email ____ By telephone ____ By other means of communication ____
______ C. We ran the experiment together, working in the same location simultaneously.
______ D. Other (If so, please describe.)
14. How did your group operate the laboratory apparatus?
______ A. One person did it. (Are you that person? Yes____ No____)
______ B. All group members took turns running it.
15. About how many data collection runs did you do (or watch) in total? ______
17. During data collection, to what extent did you feel engaged in/absorbed by the experiment?
Not at all 1 2 3 4 5 6 7 8 9 Completely
18. To what extent did you feel you had active control over the experiment?
Not at all 1 2 3 4 5 6 7 8 9 Completely
19. To what extent did you feel you could choose freely what you wanted to see?
Not at all 1 2 3 4 5 6 7 8 9 Completely
20. To what extent did you experience a sense of 'being there' inside the environment you saw/heard?
Not at all 1 2 3 4 5 6 7 8 9 Completely
27. Please estimate how much time you personally spent on each phase of the beam lab:

Reading/studying instructions:	__________ min
Equipment/software setup:	__________ min
Data collection:	__________ min
Data analysis:	__________ min
Write-up:	__________ min

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