Hands-On, Simulated, and Remote Laboratories: A Comparative Literature Review

JING MA AND JEFFREY V. NICKERSON

Stevens Institute of Technology

Laboratory-based courses play a critical role in scientific education. Automation is changing the nature of these laboratories, and there is a long-running debate about the value of hands-on versus simulated laboratories. In addition, the introduction of remote laboratories adds a third category to the debate. Through a review of the literature related to these labs in education, the authors draw several conclusions about the state of current research. The debate over different technologies is confounded by the use of different educational objectives as criteria for judging the laboratories: Hands-on advocates emphasize design skills, while remote lab advocates focus on conceptual understanding. We observe that the boundaries among the three labs are blurred in the sense that most laboratories are mediated by computers, and that the psychology of presence may be as important as technology. We also discuss areas for future research.

Categories and Subject Descriptors: K.3 [**Computing Milieux**]: Computers and Education; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*User-centered design; interaction styles (e.g., commands, menus, forms, direct manipulation); theory and methods*; J. 4 [**Computer Applications**]: Social and Behavioral Sciences

General Terms: Experimentation, Design, Performance

Additional Key Words and Phrases: Remote laboratories, experimentation, simulation, presence, thought experiments, human-computer interaction, teleoperation

1. INTRODUCTION

Increasing use of automation presents a quandary to institutions of higher learning. On the one hand, these technologies can increase the reach of pedagogy by allowing professors to teach large numbers of students who are geographically dispersed. On the other hand, automation may remove the serendipity associated with traditional laboratory learning. This quandary may be examined more specifically by looking at the debate over the value of hands-on versus simulated and remote laboratories in engineering. In this review, we will describe the multiple streams of research that address this question.

The topic may seem narrow, but we believe it is timely and has broad significance. For example, the control of a remote laboratory in a classroom is very similar to the

This research was supported by the National Science Foundation under Grant No. 0326309.

Authors' addresses: J. Ma, J. V. Nickerson, Wesley J. Howe School of Technology Management, Stevens Institute of Technology, Hoboken, NJ 07030; email: {jmal, jnickerson}@stevens.edu.

control of robots used in remote manufacturing. Thus, the topic has implications for education, robotic research, and industry.

There is no doubt that lab-based courses play an important role in scientific education. Nersessian [1991] goes so far as to claim that "hands-on experience is at the heart of science learning" and Clough [2002] declares that laboratory experiences "make science come alive." Lab courses have a strong impact on students' learning outcomes, according to Magin et al. [1986].

Researchers have convincingly argued that information technology has dramatically changed the laboratory education landscape [Scanlon et al. 2002]. The nature and practices of laboratories have been changed by two new technology-intensive automations: simulated labs [e.g., McAteer et al. 1996] and remote labs [e.g., Aburdene et al. 1991; Albu et al. 2004; Arpaia et al. 1998; Canfora et al. 2004] as alternatives for conventional hands-on labs. Each type of lab has been discussed from different perspectives [Nedic et al. 2003; Sehati 2000; Selvaduray 1995; Subramanian and Marsic 2001; Wicker and Loya 2000]. However, there is no conclusive answer to the key question: Can technology promote students' learning or not? The two new forms of laboratory are seen by some as educational enablers [Ertugrul 1998; Hartson et al. 1996; Raineri 2001; Striegel 2001] and by others as inhibitors [Dewhurst et al. 2000; Dibiase 2000]. The relative effectiveness of the two new laboratories compared with traditional hands-on labs is seldom explored.

As a backdrop for these phenomenological issues, there is a set of economic issues. Universities are struggling with the heavy financial burden of maintaining expensive apparatus in traditional laboratories and seek to maintain the effectiveness of laboratory education, while at the same time reducing the cost. Remote and simulated laboratories may provide a way to share specialized skills and resources, thereby reducing overall costs and enriching the educational experience. Educators might then satisfy economic constraints as well as produce better learning. However, in contrast to this view, a dystopian vision sees educators fooling themselves into believing the technologies are an improvement, thus depriving students of the hands-on experiences they need in order to become scientists.

Our research questions are the following: What might explain the continued unresolved debate over the effectiveness of different laboratory technologies in education? Having understood the state-of-the-art, what will be the fruitful areas for future research?

We will answer these questions through an analysis of the current research. First, we will discuss how we surveyed the literature. Next, we will make some general observations about the literature in the field, and will articulate the positions of both advocates and detractors of the different forms of laboratories. We will then provide a set of possible explanations for why the different viewpoints have not converged. In particular, we will look at an important aspect of the literature, the differing educational objectives used by advocates of different technologies. We will look at other possible explanations for the unresolved debate over the competing types of laboratories, including issues surrounding both coordination and presence, and their interaction with the choice of technology. Following this, we will discuss the implications for future research.

2. METHOD FOR THE LITERATURE SEARCH

This domain of study ranges across many disciplines, and is challenging to survey. In order to find the existing literature, we focused on three electronic databases: ACM, IEEE, and ScienceDirect. Also, we reviewed the table of contents of educational journals which publish work in this area, including *Computers and Education*, *Computers in Human Behavior, the Journal of Learning Sciences*, *Learning and Instruction*, *the*

Table I. Subjects and Methodology in the 60 Articles

	Subject			Methodology		
Lab Style	Engineering	Science	Others	Technical	Qualitative	Empirical
Hands-on	11	7	2	1	16	3
Simulated	13	4	3	14	6	0
Remote	15	2	3	17	3	0
Total	39	13	8	32	25	3

International Journal of Electrical Engineering Education, and *the International Journal of Engineering Education*. We used a list of Boolean conditional keyword phrases such as "remote laboratory or remote experiment," "virtual laboratory or virtual experiment," "real laboratory or real experiment," and "hands-on laboratory or hands-on experiment." Overall, more than 1000 articles were found. We looked through the titles of the articles to eliminate once that were unrelated; for the rest, we browsed the abstracts to gauge their relevance.

We also used other criteria to filter the literature. First, we excluded articles that discussed laboratory infrastructure without paying attention to its educational value. For example, one article we found addressed the feasibility and implementation of simulated scenarios for power systems without regard to education [Foley et al. 1990]. Also, we excluded articles which championed the use of computers to acquire data (e.g., Barnard [1985]; Staden et al. [1987]). In addition, we focused on journal rather than conference articles, and within the set of journals, we paid more attention to those with higher-impact factors. However, there was a tradeoff; many relevant educational studies take place in interdisciplinary conferences that focus on special problem domains, and these works are important to the field.

As a result, 60 articles were selected for a full-text review and coding (20 publications each for hands-on labs, simulated labs, and remote labs). These articles are listed in the Appendix. There are many high-quality, relevant articles that we did not find through this process; the articles in our list should be regarded as representative of the work written on the topic, but not in any sense as a ranking. In the course of performing the survey, we also read many other worthy articles outside of the 60, and we cite them throughout our work. A number of articles range across the boundaries of the different lab types, either because they compare them or because they discuss hybrid mixtures of laboratories. These articles do not appear in the list of 60 works, but we show them in Table II.

3. OBSERVATIONS

Our search results indicate that the attention in this field is dispersed across more than 100 different journals and conferences. One possible explanation for the scattered distribution might be the wide disciplinary spectrum of this area. Authors focus on different domains, including engineering, the natural sciences, education, and psychology. Within engineering, there is a further breakdown into electrical, mechanical, experimental, and aeronautical engineering. In the natural sciences, there are articles which focus on physics, chemistry, and biology.

3.1. Observation I—Most of the Laboratories Discussed Fall into the Engineering Domain

In order to provide a clear view of what the articles are about, we divide the literature into three separate subject categories: *engineering*, *natural science*, and *others*. Most of the literature focuses on engineering laboratories (39), as opposed to laboratories in pure science disciplines (13). Engineering contained the biggest portion of laboratory studies, as shown in Table I.

Table II. Comparison of Lab Formats

Article	C & H *	S	R	H	Sample Size	Outcome
Carlson and Sullivan [1999]	H	√	√	√	N = 3160	Overwhelming positive for integrated labs
Subramanian and Marsic [2001]	H	√		√	N = 18	Positive attitude for simulation as supplement
Gillet et al. [2005]	H	√		√	N = 96	Positive attitude of simulation as supplement
Edward [1996]	C	√		√	N = 56	Hands-on group learning superior, but simulation group is preferred**
McAteer et al. [1996]	C	√		√	N = 66	Positive attitude for simulations as alternative
Engum et al. [2003]	C	√		√	N = 163	Hands-on groups have more cognitive gains, more satisfaction**
Sonnenwald et al. 2003]	C		√	√	N = 40	Equivalence of remote labs**
Scanlon et al. [2004]	C		√	√	N = 12	Equivalence of remote labs
Corter et al. [2004]	C		√	√	N = 29	Equivalence of remote labs
Sicker et al. [2005]	C		√	√	N = 12	Equivalence of remote labs, but hands-on is preferred

*The first column indicates whether the articles evaluate hybrid combinations of labs, or strictly compare the different types; S, R, and H represent simulated, remote, and hands-on labs. **Those which discuss p statistics on the significance of tests.

Why might this be? Science professors may see laboratories as a way of confirming beliefs and teaching scientific methods. Engineering professors may also see the labs as connected to future employment [Faucher 1985]. In other words, engineering is an applied science, and the labs are a place to practice the application of scientific concepts. Also, educators in the engineering disciplines may be more likely to have the technical skills needed to create technology-enriched labs. While there are some commercial simulators available for certain engineering and science-related topics, to our knowledge there are no off-the-shelf remote laboratory systems currently available and therefore, professors who desire them are likely to develop them themselves if they have the requisite skills. Alternatively, the impetus for the creation of a remote laboratory may come from an engineer's desire to build something.

3.2. Observation II—There is No Standard Criteria to Evaluate the Effectiveness of Labwork

Given that the literature is spread across so many disciplines, it is not surprising that we did not see any agreement on conventions for evaluating the educational effectiveness of labwork. Even the definitions of hands-on labs, simulated labs, and remote labs are inconsistent and confusing. For example, remote labs are called *web* labs [Ross et al. 1997], *virtual* labs [Ko et al. 2000] or *distributed learning* labs [Winer et al. 2000] in different studies.

As a result, no common foundation has been established to evaluate the effectiveness of labwork [Psillos and Niedderer 2002]. In 1982, Hofstein and Lunetta [1982] gave a critical analysis of laboratory education, and twenty years later they published another review [2004] examining the literature published in the interim. There was no significant change. Many problems discussed in 1982 still remain unsolved, such as the absence of agreed-upon assessment measures of students' learning and insufficient sample sizes in quantitative studies. As early as 1972, Lee and Carter [1972] surveyed 20 British universities for recent changes in labwork and reported that the ill-defined objectives of undergraduate practice work were putting laboratory education into a precarious situation. They argued that clear objectives are necessary to evaluate laboratory learning outcomes.

Different approaches have been adopted for associating laboratory aims and outcomes. For example, Fisher [1977] proposed that the variance between ideal aims and actual results should be used as the assessment criterion to evaluate laboratory learning outcomes, while others [Boud 1973; Cawley 1989; Rice 1975] tried to develop a checklist of different learning aims for laboratory education and to put different weights on each of them. The effectiveness of laboratories was then evaluated by the performance on different objectives, as well as these weights. Hegarty [1978] argued that the role of the traditional laboratory should be changed and the ability to perform scientific inquiry should be addressed as the primary goal in laboratory education. More recently, four reviews have been published to examine technology-mediated practical work. Hodson [1996] and Scanlon et al. [2002] provided a general review discussing different approaches that have been used to investigate laboratory work. Ertugrul [2000b] surveyed labVIEW-based labs with respect to both simulated and remote labs; Amigud et al. [2002] covered 100 virtual laboratories in an attempt to establish the criteria for assessing virtual labs. Each of these articles provide valuable insights in studying laboratories, but only within its focus topic.

The three types of labs are sometimes compared to each other, while in other cases the labs are merged, as shown in Table II. The integrated teaching and learning (ITL) program at the University of Colorado at Boulder provided an example of how to combine hands-on practice with simulation experience and remote experimentation [Carlson and Sullivan 1999; Schwartz and Dunkin 2000]. A handful of articles evaluated remote laboratories in comparison to hands-on laboratories [Corter et al. 2004; Ogot et al. 2003; Sicker et al. 2005; Sonnewald et al. 2003] or simulated laboratories in comparison to hands-on laboratories [Engum et al. 2003]. Engum et al. [2003] showed that hands-on labs were more effective than simulated; however, we note that the problem domain, the placement of an intravenous catheter by nursing students, might reasonably be expected to require hands-on training. The general consensus of these comparison studies, with the exception of Engum et al., is that there is no significant and consistent difference between hands-on, simulated, and remote laboratories as measured by the results of lab reports or testing. For the most part, the comparative studies are small-scale.

There are many reasons why this is the case. Research across the formats holds specific challenges. Large-scale randomized studies can take place only with large numbers of students attending a class. This will tend to limit such experiments to introductory level courses which are shared across many different concentrations; such courses may not be the desired venues within which to test a new apparatus or specialized device. In addition, different technologies suggest different uses; for example, instructors may design a simulation experiment that uses color to show temperature in a way that is impossible to replicate in a hands-on lab. This may produce the most effective teaching, but it makes comparison difficult.

3.3. Observation III—There are Advocates and Detractors for Each Lab Type

As a reflection of the confusion in evaluating the effectiveness of laboratory education, the arguments about different laboratories are also inconsistent and ambiguous. We look at the discussed pros and cons of each lab type in turn.

Hands-On Labs. Hands-on labs involve a physically real investigation process. Two characteristics distinguish hands-on from the other two labs: (1) All the equipment required to perform the laboratory is physically set up; and (2) the students who perform the laboratory are physically present in the lab. Advocates argue that hands-on labs provide the students with real data and "unexpected clashes"—the disparity between theory and practical experiments that is essential in order for students to understand the role of experiments. Such experiences are missing in simulated labs [Magin and Kanapathipillai 2000].

On the other hand, hands-on experiments are seen as too costly. Hands-on labs put a high demand on space, instructor time, and experimental infrastructure, all of which are subject to rising costs [Farrington et al. 1994; Hessami and Sillitoe 1992; Philippatos and Moscato 1971]. A continuous decline in hands-on laboratory courses has been noted. The ASEE [1987] suggested that "making use of advances in information technology" might be a "cost-effective approach" towards economizing laboratory-based courses.

Also, due to the limitation of space and resources, hands-on labs are unable to meet some of the special needs of disabled students [Colwell et al. 2002] and distant users [Shen et al. 1999; Watt et al. 2002]. Additionally, students' assessments suggest that students are not satisfied with current hands-on labs [Cruickshank 1983; Dobson et al. 1995; Magin and Reizes 1990].

Simulated Labs. Simulated labs are the imitations of real experiments. All the infrastructure required for laboratories is not real, but simulated on computers. The advocates of simulated labs argue that they are not only necessary, but valuable. First, simulated labs are seen as a way to the deal with the increasing expenses of hands-on laboratories. Simulations purportedly reduce the amount of time it takes to learn. Additionally, simulated labs are seen as being at least as effective as traditional hands-on labs [Shin et al. 2002] in that "the students using a simulator are able to 'stop the world' and 'step outside' of the simulated process to review and understand it better" [Parush et al. 2002]. Furthermore, they are also embraced for creating an active mode of learning that thereby improves students' performance [Faria and Whiteley 1990; Smith and Pollard 1986; Whiteley and Faria 1989].

Detractors argue that excessive exposure to simulation will result in a disconnection between real and virtual worlds [Magin and Kanapathipillai 2000]. Data from simulated labs are not real and therefore, the students can't learn by trial-and-error [Grant 1995]. Another concern about simulation is its cost. Some note that the cost of simulation is not necessarily lower than that of real labs [Canizares and Faur 1997]. Realistic simulations take a large amount of time and expense to develop and still may fail to faithfully model reality [Papathanassiou et al. 1999]. The theory of situated learning (e.g., McLellan [1995]) would suggest that what students learn from simulations is primarily how to run simulations.

Remote Labs. Remote labs are characterized by mediated reality. Similar to hands-on labs, they require space and devices. What makes them different from real labs is the distance between the experiment and the experimenter. In real labs, the equipment might be mediated through computer control, but colocated. By contrast, in remote labs experimenters obtain data by controlling geographically detached equipment. In other words, reality in remote labs is mediated by distance.

Remote labs are becoming more popular [Fujita et al. 2003; Gustavsson 2002; Shaheen et al. 1998; Yoo and Hovis 2004]. They have the potential to provide affordable real experimental data through sharing experimental devices with a pool of schools [Sonnenwald et al. 2003; Zimmerli et al. 2003]. Also, a remote lab can extend the capability of a conventional laboratory. Along one dimension, its flexibility increases the number of times and places a student can perform experiments [Canfora et al. 2004; Hutzel 2002]. Along another, its availability is extended to more students [Cooper et al. 2000b]. Additionally, comparative studies show that students are motivated and willing to work in remote labs [Cooper et al. 2000b]. Some students even think remote labs are more effective than working with simulators [Scanlon et al. 2004].

However, even as remote labs become more popular, their educational effectiveness is being questioned. Keilson et al. [1999] point out that the equivalence between the original laboratory experiment and its remote implementation is conditional and limited. They argue that students are likely to be distracted and impatient with the computers, which in turn will harm students' engagement with the experiment. Vaidyanathan and Rochford [1998] also report that the value of remote experiments is doubted by some students. Nedic et al. [2003] suggest that students don't consider remote labs realistic, therefore, they claim that students' feelings towards both simulated and remote labs are the same, regardless of the fact that remote labs provide real data.

4. EXPLAINING THE DEBATE

4.1. Overview

We found three things: a preponderance of articles from engineering, a lack of agreement on what constitutes effectiveness in student learning, and evangelism for one or another possible format without sufficient empirical evidence. With such contradictory results, one possible explanation is that there are confounds present. If such confounds could identified, then research in the field might proceed less divisively and more rapidly.

Here, we will look for possible explanations for why researchers disagree over the relative merits of the different laboratory technologies. We have several purposes for doing this. First, for the interested reader, these possible explanations provide a way to explain in more detail what we have found in the literature. Second, for the researcher in the field, the discussion of possible confounding factors leads naturally to a discussion of possible future research to better understand which factors are important in producing a more effective laboratory education. Third, for the philosophically inclined, we will show that the issues concerning laboratory technology are related to questions about the way we interact both with the natural world and with each other.

4.2. Advocates Measure Against Different Educational Objectives

The educational objectives used to evaluate the technology differed. This led us to wonder if the controversy over the laboratories might be explained in the following way: Since advocates of the competing technologies measure against different objectives, they all can claim superiority, but each in reference to a different criterion.

In order to study this hypothesis, we first coded the articles based on educational objectives. We developed a four-dimensional goal model for laboratory education (see Table III). We built this model starting with the educational goals proposed by the Accreditation Board for Engineering and Technology (ABET) [2005]. We also considered other taxonomies of lab work [Herron 1971; McComas 1997; Newby 2002; Schwab 1964]. McComas proposed a measure based on the relative openness of laboratory problems; some experiments are close-ended, intended to demonstrate a formula, while some experiments are exploratory, where the results are not known ahead of time. This idea is related to the ABET recommendation to teach design, which is usually taught as an open-ended activity, as well as conceptual problem-solving, which is usually taught as a closed-ended task. We consolidate the many ABET educational goals into a smaller number of dimensions in Table III.

Using this inventory as a framework, we analyzed the 60 articles with regard to the educational goals identified. Often, the goals are explicitly stated. For example, conceptual understanding and professional skill development are identified by Beck [1963]. In other cases, the goals are implicit, for example, Shen et al. [1999] did not point out the aims of their study directly. Inferences about their

Table III. Educational Goals for Laboratory Learning

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

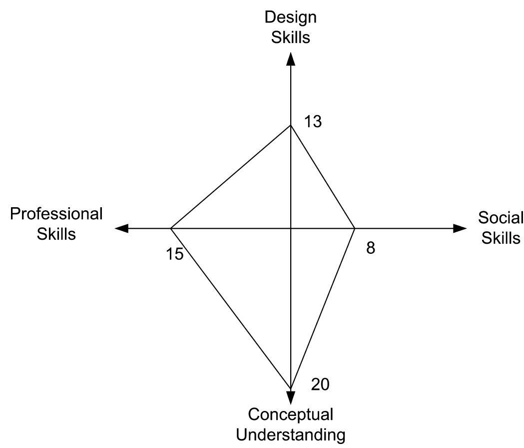

Fig. 1. Educational goals of hands-on labs.

aims can be made by analyzing the descriptions of the laboratory, the way they evaluated the laboratory, and reading between the lines in the Results and Conclusion sections.

For hands-on labs, we find that all four educational goals are well-addressed by most of the articles, as shown in Figure 1. In particular, the literature on hands-on labs placed a strong emphasis on conceptual understanding and design skills. Professional skills were also recognized as an important mission for hands-on labs.

Conceptual understanding and design skills can be regarded as opposite ends of the open-endedness scale. Numerous educators argued that design is the essential element of laboratories [Hegarty 1978; Magin and Kanapathipillai 2000; McComas 1997]. They claimed that it is critical to expose students to open-ended situations so that they develop the ability to create and investigate. We found that more than half of the hands-on laboratory articles recognized the importance of design skills and agreed that design skill is an important goal for hands-on labs.

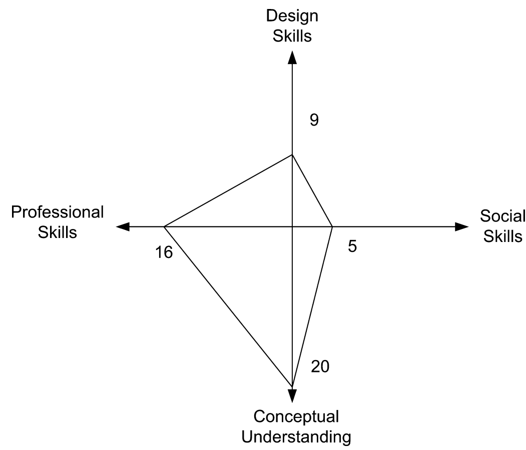

Fig. 2. Educational goals of simulated labs.

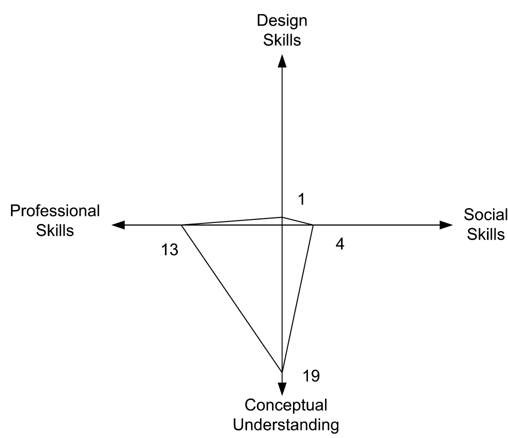

Fig. 3. Educational goals of remote labs.

The dimension of social skills is least represented in the articles. Although social skills are explicitly identified by ABET as well as other educators [Magin 1982; Edward 2002] as one of the most important goals for an engineering education, they are not discussed as often as other educational goals.

Articles on simulated laboratories skew even more towards conceptual understanding and professional skills, as shown in Figure 2. All the articles discuss conceptual understanding; less than half address design skills.

Remote laboratory articles are dramatically different, as shown in Figure 3. They focus on conceptual understanding and professional skills. Only one work discusses design skills. This is an interesting result. It suggests that the proponents of remote laboratories may think of their success only in reference to conceptual and professional learning. It may be that they do not think remote laboratories are appropriate for teaching design skills.

The results from this sample of articles suggest the following possible explanation for the debate over laboratories. Adherents of hands-on laboratories find other laboratories to be lacking. They do not believe that alternative labs can be used in teaching design skills. By contrast, adherents of remote laboratories think the hands-on laboratory researchers are ignoring evidence which shows that remote laboratories are effective in teaching concepts. Remote laboratory adherents are evaluating their own efforts with respect to teaching concepts, not design skills.

4.3. Hands-On Labs are Already Mediated by Computers

While observing a hands-on laboratory, we noticed that hands-on labs are becoming increasingly mediated. For example, an experiment may involve measuring an output through a PC connected to the experimental apparatus. In such a case, the interactive quality of laboratory participation may not differ much, whether the student is colocated with the apparatus or not. Another way to say this it is that most laboratory environments may already involve an amalgam of hands-on, computer-mediated, and simulated tools. The extent to which the interaction is already mediated may affect whether or not a remote version of the laboratory will be effective. In other words, it may depend on what is being studied. To take an extreme example, studying small objects through an electron microscope will always be mediated, and therefore, hands-on and remote lab experiences may be similar for the student.

In hands-on labs, computers are widely used to analyze data or control the experiments [Barnard 1985; Oehmke and Wepfer 1985; Saltsburg et al. 1982; Tuma et al. 1998]. From this point of view, a pure hands-on lab is rare; it is often mediated by a computer [Mann and Fung 2002]. This hybrid format of a computer-aided hands-on lab has been shown to be useful [Kasten 2000; Torres et al. 2001]. Also, simulation and remote labs may be effective in combination [Sonnenwald et al. 2003]. A variety of combinations of computers, hands-on labs, and simulations have been discussed by several researchers [Cohen and Scardamalia 1998; Riffell and Sibley 2004; Tuckman 2002]. These studies suggest that a mixture of elements might be superior to any single technology, and that what really matters might not be the type of laboratory, but the weight of each type in a given situation.

4.4. Belief May Be More Important than Technology

The effectiveness of labwork is seen to be correlated to the directness of its link to the real world [Cooper et al. 2002b; Rohrig and Jochheim 1999; Tzeng 2001]. As a result, simulated labs (and to some extent, remote labs) are criticized for their inability to provide authentic settings and interaction with real apparatus [Zeltzer 1992; Zywno and Kennedy 2000].

However, is it the link to the real world that is relevant, or the belief about that link? We examine here the possibility that it is not the actual nature of the laboratories, but the beliefs that students have about them, which may determine the effectiveness of the different lab types. We will briefly review the literature on this more philosophical issue, and relate it to the studies of laboratories.

Discussion of this issue goes back over 50 years. Two different kinds of fidelity, engineering and psychological, were clearly discerned by Miller [1954]. He noted that engineering fidelity concentrates on the closeness of simulated environments to physical surroundings, while psychological fidelity is seen as the determining factor for the effectiveness of a simulation device. More recently, Patrick [1992] reported that simulation with high psychological fidelity can lead to a high transfer of learning, despite low physical fidelity.

Table IV. Alternative Views of Presence

Article	View of Presence
Sheridan [1992]	There are three types of presence: physical presence, physically being there; telepresence, feeling as if you are actually there at the remote site of operation; and virtual presence, feeling like you are present in the environment generated by the computer.
Loomis [1992]	Presence is a mental projection of the physical object: It is not a physical state, but a phenomenal attribute that can be known only through inference.
Lombard and Ditton [1997]	Presence has six dimensions: social richness, realism, transportation, immersion, social actor, and medium.
Witmer and Singer [1998]	Presence is a perceptual flow requiring directed attention. It is based on the interaction of sensory stimulation, environmental factors, and internal tendencies.
Sheridan [1999]	Presence is "subjective mental reality." To distinguish reality from simulation, quantify the amount of noise.

The sense of being in a place is described in the literature as *presence.* Distinctions have been made between different forms of presence, as we show in Table IV. Sheridan [1992] identified three types of presence: physical, telepresence, and virtual. Physical presence is associated with real labs and understood as "physically being there." Telepresence is "feeling like you are actually there at the remote site of operation," and virtual presence is "feeling like you are present in the environment generated by the computer" (p. 120). The author argued that by suspending disbelief, we can experience presence in a virtual environment. Noel and Hunter [2000] claimed that the critical issue in designing virtual environments is to create a psychologically real setting rather than to recreate the entire physical reality. From their experiments, they concluded that by manipulating the variables of physical world, designers can create the desired subjective reality. Nunez and Blake [2003] asserted that more attention and effort should be given to the suspension of disbelief in determining presence in virtual environments.

The role of beliefs may be important in explaining students' behavior in a computer-assisted learning situation [Vuorela and Nummenmaa 2004]. It may be that psychological reality—the belief of what is real—is not restricted by physical reality and therefore, may play an important role in affecting subjects' behaviors in a virtual environment. Bradner and Mark [2001] found that subjects tend to cooperate less with their experiment partners if they believe them to be in a remote city, even if in actuality, both are in the same location.

Given the richness of information available to participants in the lab, it has often been argued that physical presence is preferred by students [Ijsselsteijn et al. 2000; Lombard and Ditton 1997; Short et al. 1976; Snow 1996]. However, remote labs and simulations provide alternate forms of presence: Telepresence and virtual presence are competitors for physical presence. Biocca [2001] claimed that the root of presence lies in the "perception of reality," rather than in physical reality. In other words, presence is more about "the illusion of being here or there and less about being as such" (p. 550), a sentiment also echoed by Bentley et al. [2003]. Slater and Usoh [1993] showed that the extent to which human participants feel immersed in virtual environments depends on how convinced they are by the computer-synthesized effects.

Some researchers have asserted that the sense of presence can predict the level of performance. By comparing experimental results under six versions of virtual environments, Bystrom and Barfield [1999] claimed that a sense of presence is one of the key contributing factors to higher task performance. Other research also provides positive support for this argument. Barfield and Weghorst [1993] illustrate the relationship between presence and performance by introducing the mediating effect of *enjoyment*.

Nevertheless, the causal relationship between presence and performance has been questioned by other researchers. Mania and Chalmers [2001], in comparing levels of presence and task performance in a real versus simulated world, suggested that presence is not necessarily positively related with task performance: High-fidelity simulations should function as well as the real world. A recent study conducted by Youngblut and Huie [2003] reported that no significant difference in task performance can be attributed to a difference in presence. Nash et al. [2000] suggested that presence alone cannot explain the difference in performance. Several studies have shown that students may prefer remote laboratories in terms of convenience, but think the interaction lacks either verisimilitude [Ogot et al. 2003] or immersion [Corter et al. 2004]. These studies, however, did not show a difference in performance.

At the extreme, experimentation can be completely independent of the physical. Thought (Gedanken) experiments also have strong advocates: "Experimenting in thought is important not only for the professional inquirer, but also for mental development" [Matthews 1991]. Reiner and Gilbert [2000] showed that thought experiments are instrumental tools for science teaching and that students who use them are able to generate new knowledge by retrieving tacit, implicit knowledge. They emphasized that thought experiments are characterized by a combination of thought and experimentation, which cannot be completely represented by either. As an extension, they further claimed that other educational elements can be integrated with thought experiments to produce hybrid experimentation, which they call *thought simulation*.

The aforementioned work in total suggests that students' preferences, and perhaps their learning performance, cannot be attributed to the technology of the laboratory alone. In other words, it is important to focus on how students' mental activities are engaged in coping with the laboratory world. From this point of view, other factors discussed in relation to the effectiveness of laboratories, such as motivation [Edward 2002], peer collaboration [Baxendale and Mellor 2000], error-corrective feedback [Grant 1995] and richness of the media [Chaturvedi et al. 2003] should also be studied in order to produce more interactive and immersive settings that ultimately lead to a space students perceive as real.

From these studies, we might expect that students in a simulated or remote lab where the reality is, respectively, faked or mediated by distance may experience psychological presence, but not physical presence. In a similar way, students in a real hands-on experiment could be exposed to physically real apparatus, but may not experience psychological presence. For example, student might get bored or distracted if their role is only to passively watch others interact with the device. Such ideas might be tested by simple framing. By changing students' beliefs about a technology (is it real or not?), as well as their ability to immerse themselves (can they interact with it or not?), the potential confounds related to belief and interactive immersion might be separated and discarded.

4.5. Collaboration Methods May Interact with the Laboratory Technology Type

Finholt and Olson [1997], echoing our previous discussion about psychological and physical reality, suggested that "laboratories as physical settings may have become less essential for scientific collaboration than was formerly the case" (p. 28). Apparently, they place an emphasis on psychology, rather than the physical locations of collaboration. *Collaboratories* (the word combination of collaboration and laboratory) have gained increased attention. They are intended to link scientists and engineers with remote facilities "as if they were colocated" [Lederberg and Uncapher 1989] to access experimental apparatus. The number of collaboratories has been increasing after a national call in 1993 to develop, refine, and evaluate the collaboratory concept in realistic settings [Agarwal et al. 1998].

The Grid project [Foster et al. 2001] builds "coordinated resources sharing" across the boundaries of multiinstitutions," which fits the premise of remote labs and collaboratories. Recognizing the impact of the grid on collaboration, researchers are trying to build "truly collaborative, multidisciplinary and multi-institutional problem-solving settings" [Mann and Parashar 2002].

The growth of this shared infrastructure in scientific practice has implications for pedagogy. First, for students who end up in careers in engineering and science, it is likely that they will at some point participate in collaboratories. Second, it may be that the collaboration, not the technology, accounts for learning performance differences. In other words, even if remote labs are not as effective as hands-on labs, the experience of working with geographically separated colleagues and specialized equipment may be educationally important enough to compensate for any shortcomings in the technology.

It may be that students using remote laboratories will find different ways of collaborating, and the mode of collaboration they choose may affect what they learn from the laboratory experience. Some researchers have begun layering coordination technologies on top of remote laboratories as part of their evaluation experiments [Scanlon et al. 2004]. There are more studies possible: For example, students might be asked to run remote laboratories separately, and then meet the next day to discuss results. The work of Pea [1993, 1994, 2002] is especially informative. He showed that the transformative communication both between students and between students and teachers is a key contributor to learning performance. He related this communication to the general concept of sensemaking, much studied in the field of organizational behavior [Weick 1996]. This work demonstrated the value of well-constructed group activities used in conjunction with simulations, as well as the feasibility of developing design skills through simulations.

5. DISCUSSION

We have looked at several possible reasons for why the debates over laboratory technology have continued over the years without any sign of abating. Our general conclusion is that researchers are confounding many different factors, and perhaps over-attributing learning success to the technologies used. There is much in the literature to suggest that both students' preferences and learning outcomes are the result of many intertwined factors. Thus, it is sensible to suggest that researchers more carefully isolate and study the different factors which might interact with laboratory technology in determining educational effectiveness. However, such work is difficult. It is hard to perform large-scale educational tests and hold factors such as instructor ability constant. It is also difficult to compare studies which focus on different scientific domains. Thus, it is especially important that effort should be focused on areas that look the most promising.

First, research may look at hybrids of laboratories that are designed to accomplish a portfolio of educational objectives. There is a fair amount of evidence that simulated and remote labs are effective in teaching concepts. There is still a shortage of data on whether such technologies are as effective as hands-on laboratories when it comes to teaching design skills. Those who advocate the use of hands-on labs might be more amenable to the use of simulated or remote technologies if all three technologies are clearly integrated as part of a curriculum in which goals such as teaching open-ended design are clearly protected. Right now, the perception is that new technologies are competitors against current teaching techniques, and this sense is probably getting in the way of a more carefully considered educational evaluation.

Second, the effectiveness of laboratories may be affected by how much students believe in them. Therefore, an understanding of presence, interaction, and belief may lead to better interfaces. Also, if belief proves important, then hybrid approaches might be contemplated, in which hands-on work is used at an early stage to build confidence in remote or simulated technology used in later teaching.

Third, research might pay more attention to collaboration and sensemaking. The technology may change the way we can and should coordinate our work, and studies of such interactions may be productive in suggesting the kinds of educational processes that should accompany the lab technologies.

6. CONCLUSION

Interest in the effectiveness of virtual versus traditional learning in laboratories has increased, probably due to two forces: advances in technology, and cost pressures on universities that are related to laboratories. In this survey, we reviewed current research on laboratory education with a focus on three different types of labs: real, simulated, and remote. We found that most of the laboratory articles were engineering-related. Additionally, there were advocates and detractors for each different type of laboratory. We asked what might explain the continued unresolved debate.

The debate can be partially explained by examining the educational objectives associated with each laboratory type. Hands-on lab adherents emphasize the acquisition of design skills as an important educational goal, while remote laboratory adherents do not evaluate their own technology with respect to this objective.

The debate is also confused for other reasons. Even hands-on laboratories are often mediated by computer, so that there is rarely a pure hands-on experience for students. Therefore, we may really be talking about relative degrees of hands-on, simulation, and remoteness. Furthermore, research in psychology suggests that the beliefs and experiences of students may be determined more by the nature of the interfaces than by the objective reality of the laboratory technology. This is a complex issue; it may be that hands-on labs are important initially to establish the reality of remote laboratories or the accuracy of simulations for later study.

Finally, it is clear that students learn not only from equipment, but from interactions with peers and teachers. New technologies may call for new forms of coordination to augment or compensate for the potential isolation of students engaged in remote learning.

Our work may provide a starting place for researchers involved in the discussion about the role and value of laboratory work. Perhaps a sense of reality can be achieved by students not only in hands-on experience, but also in virtual environments. Perhaps with the proper mix of technologies we can find solutions that meet the economic constraints of laboratories by using simulations and remote labs to reinforce conceptual understanding, while at the same time providing enough open-ended interaction to teach design. Our review suggests that there is room for research that seeks to create such a mix, which might be informed by studies of coordination as well as the interactions that lead students to a sense of immersion.

APPENDIX

TABLES OF ARTICLES AND EDUCATIONAL OBJECTIVES DISCUSSED THEREIN

Subject*
P: Physics
B: Biology
AE: Aeronautical Engineering
CE: Chemical Engineering (chemistry)
Clm: Climatology
CVE: Civil Engineering
EE: Electrical Engineering
INS: Interdisciplinary
ME: Mechanical Engineering
MME: Mechanical and Manufacturing Engineering
PE: Power Engineering
Phy: Physiology
TE: Telecommuncation
CS: Computer Science
IS: Internet Science
EES: Environmental and ecological science
SE: Science and Engineering (physics, biology, EE)

Methodology*
Qualitative—conceptualization and evaluation
Empirical—variance-based methods
Technical—design and implementation

Table V. Hands-On Laboratory Article Objectives

	Lab Style					Constraints		Educational Objectives			
Article	HL	SL	RL	Subject*	Methodology*	Time & Cost	Accessibility Flexibility	Conceptual Understanding	Professional Skills	Design Skills	Social Skills
[1]	√			ME	Q	√	√	√	√		√
[2]	√			ME	Q	√		√	√		
[3]	√			ME	E			√	√	√	√
[4]	√			ME	Q	√		√	√	√	
[5]	√			EE	Q			√	√	√	√
[6]	√			MME	Q	√	√	√		√	
[7]	√			ME	E			√	√	√	
[8]	√			SE	Q	√		√	√	√	
[9]	√			CE	E			√		√	
[10]	√			B	Q			√			√
[11]	√			EE	Q			√	√	√	
[12]	√			EE	Q	√		√	√	√	√
[13]	√			CE	Q			√	√		√
[14]	√			P	Q/T			√	√		
[15]	√			CE	Q			√	√	√	√
[16]	√			P	Q			√			
[17]	√			AE	Q			√	√	√	
[18]	√			EES	Q			√	√	√	
[19]	√			CE	Q			√			
[20]	√			ME	Q			√	√	√	√
sum						6	2	20	15	13	8

Table VI. Hands-On Laboratory Article Cross-Reference

HL-No	
1	Grant [1995]
2	Collins [1986]
3	Fisher [1977]
4	Faucher [1985]
5	Edward [2002]
6	Magin and Kanapathipillai [2000]
7	Magin [1984]
8	Elton [1983]
9	Berg et al. [2003]
10	Tapper [1999]
11	Martin and Lewis [1968]
12	Martin [1969]
13	Miller et al. [1998]
14	Beck [1963]
15	Drake et al. [1994]
16	Roth et al. [1997]
17	Wentz and Snyder [1974]
18	Schauble et al. [1995]
19	Kozma et al. [2000]
20	Feisel and Rosa [2005]

Table VII. Simulated Laboratory Article Objectives

Article	Lab Style			Subject	Methodology	Constraints		Educational Objectives			
	HL	SL	RL			Time & Cost	Accessibility Flexibility	Conceptual Understanding	Professional Skills	Design Skills	Social Skills
[1]		√		EE	T		√	√		√	
[2]		√		TE	T			√	√	√	√
[3]		√		EE	T	√	√	√	√	√	
[4]		√		EE	T	√	√	√	√		
[5]		√		ME	T	√		√			
[6]		√		EE	Q	√		√	√	√	
[7]		√		CE	T	√	√	√			
[8]		√		ME	Q			√	√	√	√
[9]		√		ME	Q	√		√	√	√	
[10]		√		Phy	Q	√	√	√	√		
[11]		√		ME	Q			√	√	√	
[12]		√		INS	T	√	√	√	√		
[13]		√		CE	T	√	√	√			√
[14]		√		B	T	√	√	√	√	√	
[15]		√		Clm	Q		√	√	√	√	√
[16]		√		CVE	T	√	√	√	√		
[17]		√		ME	T	√	√	√	√		
[18]		√		PE	T	√		√	√		√
[19]		√		PE	T			√	√		
[20]		√		PE	T			√	√		
sum						13	11	20	16	9	5

Table VIII. Simulated Laboratory Article Cross-Reference

SL-No	Article
1	Chetty and Dabke [2000]
2	Fernandez-Inglesias et al. [2000]
3	Sehati [2000]
4	Ertugrul [1998]
5	Wicker and Loya [2000]
6	Smith and Pollard [1986]
7	Garcya-Luque et al. [2004]
8	Edward [1996]
9	Dobson et al. [1995]
10	McAteer et al. [1996]
11	Magin and Reizes [1990]
12	Shin et al. [2002]
13	Gomes et al. [2000]
14	Raineri [2001]
15	Edleson et al. [1999]
16	Budhu [2000]
17	Ertugrul [2000a]
18	Karady et al. [2000a]
19	Karady et al. [2000b]
20	Sakis Meliopoulos and Cokkinides [2000]

Table IX. Remote Laboratory Article Objectives

	Lab Style					Constraints		Educational Objectives			
Article	HL	SL	RL	Subject	Methodology	Time & Cost	Accessibility Flexibility	Conceptual Understanding	Professional Skills	Design Skills	Social Skills
[1]			√	ME	T	√	√	√	√		
[2]			√	ME	T	√	√	√			
[3]			√	EE	T	√	√	√	√		
[4]			√	EE	T			√	√		
[5]			√	IS	T	√	√	√	√		
[6]			√	EES	T	√	√	√			
[7]			√	EE	T		√	√			
[8]			√	EE	T	√	√	√	√		
[9]			√	EE	T	√	√	√	√		
[10]			√	EE	T	√	√	√			
[11]			√	EE	T	√	√	√	√		
[12]			√	EE	T	√	√	√	√		
[13]			√	SE	Q	√	√	√	√		√
[14]			√	P & CE	Q	√	√	√	√		
[15]			√	CS	T	√	√	√	√		√
[16]			√	EE	T	√	√				
[17]			√	B	Q	√	√	√	√	√	√
[18]			√	EE	T		√	√			
[19]			√	EE	T	√	√	√			√
[20]			√	EE	T	√	√	√	√		
sum						17	19	19	13	1	4

Table X. Remote Laboratory Article Cross-Reference

RL-No	Article
1	Tan et al. [2000]
2	Hutzel [2002]
3	Gustavsson [2003]
4	Vial and Doulai [2003]
5	Naghdy et al. [2003]
6	Krehbiel et al. [2003]
7	Shen et al. [1999]
8	Arpaia et al. [2000]
9	Ferrero et al. [2003]
10	Albu et al. [2004]
11	Gustavsson [2002]
12	Bauchspiess et al. [2003]
13	Colwell et al. [2002]
14	Scanlon et al. [2004]
15	Zimmerli et al. [2003]
16	Arpaia et al. [1997]
17	Thakkar et al. [2000]
18	Ko et al. [2000]
19	Rohrig and Jochheim [2001]
20	Kolberg and Fjeldly [2004]

ACKNOWLEDGMENTS

We wish to thank the principle investigator of our NSF-sponsored research project, Sven Esche, and our coinvestigators, Constantin Chassapis and James Corter. We also thank Elizabeth Watson and Richard Reilly for their suggestions.

REFERENCES

ABET. 2005. Criteria for accrediting engineering programs. Retrieved 10-25-05 from http://www.abet.org/Linked%20Documents-UPDATE/Criteria%20and%20PP/05-06-EAC%20Criteria.pdf.

ABURDENE, M. F., MASTASCUSA, E. J., AND MASSENGALE, R. 1991. A proposal for a remotely shared control systems laboratory. In *Proceedings of the Frontiers in Education 21st Annual Conference*. West Lafayette, IN. 589–592.

AGARWAL, D. A., SACHS, S. R., AND JOHANSTON, W. E. 1998. The reality of collaboratories. *Comput. Physt. Commun. 110*, 134–141.

ALBU, M. M., HOLBERT, K. E., HEYDT, G. T., GRIGORESCU, S. D., AND TRUSCA, V. 2004. Embedding remote experimentation in power engineering education. *IEEE Trans. Power Syst. 19*, 1, 139–143.

AMIGUD, Y., ARCHER, G., SMITH, J., SZYMANSKI, M., AND SERVATIUS, B. 2002. Assessing the quality of web-enabled laboratories in undergraduate education. In *Proceedings of the 32nd ASEE/IEEE Frontiers in Education Conference*. Boston, MA. 12–16.

ARPAIA, P., BACCIGALUPI, A., CENNAMO, F., AND DAPONTE, P. 1997. A remote measurement laboratory for educational experiments. *Measurement 21*, 4, 157–169.

ARPAIA, P., BACCIGALUPI, A., CENNAMO, F., AND DAPONTE, P. 1998. A measurement laboratory on geographic network for remote test experiments. In *Proceedings of the 1998 IEEE Conference on Instrumentation and Measurement Technology*. 206–209.

ARPAIA, P., BACCIGALUPI, A., CENNAMO, F., AND DAPONTE, P. 2000. A measurement laboratory on geographic network for remote test experiments. *IEEE Trans. Instrumentation and Measurement 49*, 5, 992–997.

ASEE. 1987. The national action agenda for engineering education: A summary. *Eng. Education 78*, 2, 95–99.

BARFIELD, W. AND WEGHORST, S. 1993. The sense of presence within virtual environments: A conceptual framework. In *Human Computer Interaction: Software and Hardware Interfaces*, G. Salvendy and M. Smith, Eds. Elsevier, 699–704.

BARNARD, R. H. 1985. Experience with low cost laboratory data. *Int. J. Mechanical Eng. Education 13*, 91–96.

BAUCHSPIESS, A., GUIMARAES, B., AND GOSMANN, H. L. 2003. Remote experimentation on three coupled water reservoirs. In *Proceedings of the 2003 IEEE International Symposium on Industrial Electronics*. 572–577.

BAXENDALE, P. AND MELLOR, J. 2000. A 'virtual laboratory' for research training and collaboration. *Int. J. Electrical Eng. Education 37*, 1, 95–107.

BECK, H. V. 1963. Practical class work at the Cavendish laboratory. *Contemporary Phy. 4*, 206–220.

BENTLEY, F., TOLLMAR, O., DEMIRDJIAN, D., OILE, K., AND DARRELL, T. 2003. Perceptive presence. *IEEE Comput. Graph. Appl. 23*, 5, 26–36.

BERG, C. A. R., BERGENDAHL, V. C. B., LUNDBERG, B. K. S., AND TIBELL, L. A. E. 2003. Benefiting from an open-ended experiment? A comparison of attitudes to, and outcomes of, an expository versus an open-inquiry version of the same experiment. *Int. J. Sci. Education 25*, 3, 351–372.

BIOCCA, F. 2001. Inserting the presence of mind into a philosophy of presence: A response to Sheridan and Mantovaniand Riva. *Presence: Teleoper. Virtual Environ. 10*, 5, 546–556.

BOUD, D. J. 1973. The laboratory aims questionnaire—A new method for course improvement? *Higher Education 2*, 81–94.

BRADNER, E. AND MARK, G. 2001. Social presence with video and application sharing. In *Proceedings of the 2001 International ACM SIGGROUP Conference on Supporting Group Work*. Boulder, Colorado. ACM Press, New York, 154–161.

BUDHU, M. 2000. Interactive multimedia web-based courseware with virtual laboratories. In *Proceedings of the CATE Computers and Advanced Technology in Education 2000 Conference*. Cancun, Mexico. 19–25.

BYSTROM, K. E. AND BARFIELD, W. 1999. Collaborative task performance for learning using a virtual environment. *Presence: Teleoper. Virtual Environ. 8*, 4, 435–448.

CANFORA, G., DAPONTE, P., AND RAPUANO, S. 2004. Remotely accessible laboratory for electronic measurement teaching. *Comput. Standards and Interfaces 26*, 6, 489–499.

CANIZARES, C. A. AND FAUR, Z. T. 1997. Advantages and disadvantages of using various computer tools in electrical engineering courses. *IEEE Trans. Education 40*, 3, 166–171.

CARLSON, L. E. AND SULLIVAN, J. F. 1999. Hands-on engineering: Learning by doing in the integrated teaching and learning program. *Int. J. Eng. Education 15*, 1, 20–31.

CAWLEY, P. 1989. Is laboratory teaching effective? *Int. J. Mechanical Eng. Education 17*, 15–27.

CHATURVEDI, S., AKAN, O., BAWAB, S., ABDEJ-SALAM, T., AND VENKATARAMANA, M. 2003. A web-based multimedia virtual experiment. In *Proceedings of the 33rd ASEE/IEEE Frontiers in Education Conference*. Boulder, CO. T3F.3-T3F.8.

CHETTY, M. AND DABKE, K. P. 2000. Towards a web-based control engineering. *Int. J. Electrical Eng. Education 37*, 1, 39–47.

CLOUGH, M. P. 2002. Using the laboratory to enhance student learning. In *Learning Science and the Science of Learning*, R. W. Bybee, Ed. National Science Teachers Association, Washington, DC, 85–97.

COHEN, A. AND SCARDAMALIA, M. 1998. Discourse about ideas: Monitoring and regulation in face-to-face and computer-mediated environments. *Interactive Learning Environ. 6*, 1–2, 93–113.

COLLINS, J. J. 1986. Reflections on teaching experimentation to "applications" engineering undergraduates. *Int. J. Mechanical Eng. Education 14*, 175–182.

COLWELL, C., SCANLON, E., AND COOPER, M. 2002. Using remote laboratories to extend access to science and engineering. *Comput. and Education 38*, 1–3, 65–76.

COOPER, M., COLWELL, C., AND AMARAL, T. 2002a. Accessibility and usability in complex web based learning applications: Lessons from the PEARL project. In *Proceedings of the Corporations, Government, Health, and World Conference on E-Learning in Higher Education*. Montreal, Canada. 1358–1365.

COOPER, M., DONNELLY, A., AND FERREIRA, J. M. 2002b. Remote controlled experiments for teaching over the Internet: A comparison of approaches developed in the PEARL project. In *Proceedings of the ASCILITE Conference 2002*. Auckland, New Zealand. UNITEC Institution of Technology, M2D.1-M2D.9.

CORTER, J. E., NICKERSON, J. V., ESCHE, S. K., AND CHASSAPIS, C. 2004. Remote versus hands-on labs: A comparative study. In *Proceedings of the 34th ASEE/IEEE Frontiers in Education Conference*. Savannah, GA. F1G.17-F1G.21.

CRUICKSHANK, A. J. B. 1983. A teaching-laboratory experiment. *Comput. and Education 7*, 4, 209–222.

DEWHURST, D. G., MACLEOD, H. A., AND NORRIS, T. A. M. 2000. Independent student learning aided by computers: An acceptable alternative to lectures? *Comput. and Education 35*, 3, 223–241.

DIBIASE, D. 2000. Is distance teaching more work or less work? *American J. Distance Education 14*, 3, 6–20.

DOBSON, E. L., HILL, M., AND TURNER, J. D. 1995. An evaluation of the student response to electronics teaching using a CAL package. *Comput. and Education 25*, 1–2, 13–20.

DRAKE, B. D., ACOSTA, G. M., WINGARD, D. A., AND R. L. SMITH, J. 1994. Improving creativity, solving problems and communications with peers in engineering science laboratories. *J. Chemical Education 71*, 7, 592–596.

EDLESON, D. C., GORDIN, D. N., AND PEA, R. D. 1999. Addressing the challenges of inquiry-based learning through technology and curriculum design. *J. Learning Sci. 8*, 3 and 4, 391–450.

EDWARD, N. S. 1996. Evaluation of computer based laboratory simulation. *Comput. and Education 26*, 1–3, 123–130.

EDWARD, N. S. 2002. The role of laboratory work in engineering education: Student and staff perceptions. *Int. J. Electrical Eng. Education 39*, 1, 11–19.

ELTON, L. 1983. Improving the cost-effectiveness of laboratory teaching. *Studies in Higher Education 8*, 79–85.

ENGUM, S. A., JEFFRIES, P., AND FISHER, L. 2003. Intravenous catheter training system: Computer-Based education versus traditional learning methods. *American J. Surgery 186*, 1, 67–74.

ERTUGRUL, N. 1998. New era in engineering experiments: An integrated and interactive teaching/learning approach, and real-time visualizations. *Int. J. Eng. Education 14*, 5, 344–355.

ERTUGRUL, N. 2000a. Cost effective and advanced teaching laboratory development at the University of Adelaide. In *Proceedings of the IASTED International Conference on Computers and Advance Technology in Education*. Cancun, Mexico. 188–193.

ERTUGRUL, N. 2000b. Towards virtual laboratories: A survey of LabVIEW-Based teaching/learning tools and future trends. *Int. J. Eng. Education 16*, 3, 171–180.

FARIA, A. J. AND WHITELEY, T. R. 1990. An empirical evaluation of the pedagogical value of playing a simulation game in a principles of marketing course. *Development in Business Simul. Experiential Learning 17*, 53–57.

FARRINGTON, P. A., MESSIMER, S. L., AND SCHROER, B. J. 1994. Simulation and undergraduate engineering education: The technology reinvestment project (TRP). In *Proceedings of the 1994 Winter Simulation Conference*. Lake Buena Vista, FL. J. D. Tew et al., Eds. 1387–1393.

FAUCHER, G. 1985. The role of laboratories in engineering education. *Int. J. Mechanical Eng. Education 13*, 195–198.

FEISEL, L. D. AND ROSA, A. J. 2005. The role of the laboratory in undergraduate engineering education. *J. Eng. Education*, 121–130.

FERNANDEZ-INGLESIAS, M. J., GONZALEZ-CASTANO, F. J., AND POUSADA-CARBALLO, J. M. 2000. An undergraduate low-level computer communications laboratory oriented towards industry. *Int. J. Electrical Eng. Education 37*, 2, 146–156.

FERRERO, A., SALICONE, S., BONORA, C., AND PARMIGIANI, M. 2003. ReMLab: A Java-Based remote, didactic measurement laboratory. *IEEE Trans. Instrumentation and Measurement 52*, 3, 710–715.

FINHOLT, T. AND OLSON, G. 1997. From laboratories to collaboratories: A new organizational form for scientific collaboration. *Psychological Sci. 8*, 1, 28–36.

FISHER, B. C. 1977. Evaluating mechanical engineering laboratory work. *Int. J. Mechanical Eng. Education 5*, 147–157.

FOLEY, M., CHEN, Y., AND BOSE, A. 1990. A modern digital simulation laboratory for power systems. *IEEE Comput. Appl. Power 3*, 2, 16–19.

FOSTER, I., KESSELMAN, C., AND TUECKE, S. 2001. The anatomy of the grid: Enabling scalable virtual organizations. *Int. J. Supercomput. Appl. 15*, 3, 1–25.

FUJITA, J. S. T., CASSANIGA, R. F., AND FERNANDEZ, F. J. R. 2003. Remote laboratory. In *Proceedings of the 2003 IEEE International Symposium on Industrial Electronics*. Rio. de Janeiro, Brazil. 1104–1106.

GARCYA-LUQUE, E., ORTEGA, T., FORJA, J. M., AND GOMEZ-PARRA, A. 2004. Using a laboratory simulator in the teaching and study of chemical processes in estuarine systems. *Comput. and Education 43*, 81–90.

GILLET, D., NGUYEN, A. V., AND REKIK, Y. 2005. Collaborative web-based experimentation in flexible engineering education. *IEEE Trans. Education PP 99*, 1–9.

GOMES, V. G., CHOY, B., BARTON, G. W., AND ROMAGNOLI, J. A. 2000. Web-based courseware in teaching laboratory-based courses. *Global J. Eng. Education 4*, 1, 65–71.

GRANT, A. 1995. The effective use of laboratories in undergraduate courses.*Int. J. Mechanical Eng. Education 23*, 2, 95–101.

GUSTAVSSON, I. 2002. Remote laboratory experiments in electrical engineering education. In *Proceedings of the 4th International Caracas Conference on Devices, Circuits and Systems* (*ICCDCS 2002*). Aruba. I025.1–I025.5.

GUSTAVSSON, I. 2003. A remote access laboratory for electrical circuit experiments. *Int. J. Eng. Education 19*, 3, 409–419.

HARTSON, H. R., CASTILLO, J. C., KELSO, J., AND NEALE, W. C. 1996. Remote evaluation: The network as an extension of the usability laboratory. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Common Ground*. Vancouver, Canada. 228–235.

HEGARTY, E. H. 1978. Levels of scientific inquiry in university science laboratory classes: Implications for curriculum deliberations. *Research Sci. Education 8*, 45–57.

HERRON, M. D. 1971. The nature of scientific enquiry. *School Review 79*, 2, 171–212.

HESSAMI, M. AND SILLITOE, J. 1992. The role of laboratory experiments and the impact of high-tech equipment on engineering education. *Australasian J. Eng. Education 3*, 119–126.

HODSON, D. 1996. Laboratory work as scientific method: Three decades of confusion and distortion. *J. Curriculum Studies 28*, 115–135.

HOFSTEIN, A. AND LUNETTA, V. 1982. The role of the laboratory in science teaching: Neglected aspects of research. *Review of Education Research 52*, 201–218.

HOFSTEIN, A. AND LUNETTA, V. N. 2004. The laboratory in science education: Foundations for the Twenty-First Century. *Sci. Education 88*, 1, 28–54.

HUTZEL, W. J. 2002. A remotely accessed HVAC laboratory for distance education. *Int. J. Eng. Education 18*, 6, 711–716.

IJSSELSTEIJN, W. A., RIDDER, H. D., FREEMAN, J., AND AVONS, S. E. 2000. Presence: Concept, determinants and measurement. In *Proceedings of the SPIE, Human Vision and Electronic Imaging V Conference*. San Jose, CA. 3959–3976.

KARADY, G. G., HEYDT, G. T., OLEJNICZAK, K. J., MANTOOTH, H. A., IWAMOTO, S., AND CROW, M. L. 2000a. Role of laboratory education in power engineering: Is the virtual laboratory feasible? I. In *Proceedings of the 2000 IEEE Power Engineering Society Summer Meeting*. 1471–1477.

Karady, G. G., Reta-Hernandez, M., and Bose, A. 2000b. Role of laboratory education in power engineering: Is the virtual laboratory feasible? II. In *Proceedings of the 2000 IEEE Power Engineering Society Summer Meeting*. 1478–1483.

Kasten, D. G. 2000. Integrating computerized data acquisition and analysis into an undergraduate electric machines laboratory. In *Proceedings of the 30th ASEE/IEEE Frontiers in Education Conference*. Kansas City, MO. T1D.13–T1D.18.

Keilson, S., King, E., Sapnar, M. I. S., King, E., and Sapnar, M. 1999. Learning science by doing science on the web. In *Proceedings of the 29th ASEE/IEEE Frontier in Education Conference*. San Juan, Puerto Rico., 13d4.7–13d4.12.

Kolberg, S. and Fjeldly, T. A. 2004. Web services remote educational laboratory. In *Proceedings of the International Conference on Engineering Education*. Gainesville, FL. 1–6.

Ko, C. C., Chen, B. M., Chen, S. H., Ramakrishnan, V., Chen, R., Hu, S. Y., and Zhuang, Y. 2000. A large-scale web-based virtual oscilloscope laboratory experiment. *Eng. Sci. Education J. 9*, 2, 69–76.

Kozma, R., Chin, E., Russell, J., and Marx, N. 2000. The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *J. Learning Sci. 9*, 2, 105–143.

Krehbiel, D., Zerger, R., and Piper, J. K. 2003. A remote-access LabVIEW-Based laboratory for environmental and ecological science. *Int. J. Eng. Education 19*, 3, 495–502.

Lederberg, J. and Uncapher, K. 1989. Towards a national collaboratory. *Report of an Invitational Workshop at Rockefeller University*. Washington, DC.

Lee, S. L. and Carter, G. 1972. A sample survey of departments of electrical engineering to determine recent significant changes in laboratory work patterns at first year level. *Int. J. Electrical Eng. Education 10*, 131–135.

Lombard, M. and Ditton, T. 1997. At the heart of it all: The concept of presence. *J. Comput. Mediated Commun. 3*, 2. Online journal.

Loomis, J. M. 1992. Presence and distal attribution: Phenomenology, determinants and assesment. In *Proceedings of SPIE 1992.* Boston, MA. 590–595.

Magin, D. J. 1982. Collaborative peer learning in the laboratory. *Studies in Higher Education 7*, 105–117.

Magin, D. J. 1984. Confidence and critical awareness as factors in the development of experimentation skills in laboratory courses. *Higher Education 13*, 275–288.

Magin, D. J., Churches, A. E., and Reizes, J. A. 1986. Design and experimentation in undergraduate mechanical engineering. In *Proceedings of a Conference on Teaching Engineering Designers*. Sydney, Australia. Institution of Engineers, 96–100.

Magin, D. J. and Kanapathipillai, S. 2000. Engineering students' understanding of the role of experimentation. *European J. Eng. Education 25*, 4, 351–358.

Magin, D. J. and Reizes, J. A. 1990. Computer simulation of laboratory experiments: An unrealized potential. *Comput. and Education 14*, 3, 263–270.

Mania, K. and Chalmers, A. 2001. The effects of levels of immersion on memory and presence in virtual environments: A reality centered approach. *Cyber Psychology and Behavior 4*, 2, 247–264.

Mann, S. and Fung, J. 2002. Mediated reality. *Presence: Teleoper. Virtual Environ. 11*, 2, 158–175.

Mann, V. and Parashar, M. 2002. Engineering an interoperable computational collaoratory on the grid. *Concurrency and Computation: Practice and Experience 14*, 1569–1593.

Martin, D. G. 1969. Ends and means in laboratory teaching. *Bulletin of Mechanical Eng. Education 8*, 185–189.

Martin, D. G. and Lewis, J. C. 1968. Effective laboratory teaching. *Bulletin of Mechanical Eng. Education 7*, 51–57.

Matthews, M. R., Ed. 1991. *History, Philosophy, and Science Teaching.* OISE Press, Toronto, Canada.

McAteer, E., Neil, D., Barr, N., Brown, M., Draper, S., and Henderson, F. 1996. Simulation software in a life sciences practical laboratory. *Comput. and Education 26*, 1–3, 102–112.

McComas, W. F. 1997. The nature of the laboratory experience: A guide for describing, classifying and enhancing hands-on activities. *CSTA J., Spring*, 6–9.

McLellan, H. 1995. *Situated Learning Perspectives*. Educational Technology, Englewood Cliffs, NJ.

Miller, R. B. 1954. *Psychological Considerations in the Designs of Training Equipment*. Wright Air Development Center, Wright Patterson AFB, OH.

Miller, R. L., Ely, J. F., Baldwin, R. M., and Olds, B. M. 1998. Higher-Order thinking in the unit operations laboratory. *Chemical Eng. Education 32*, 2, 146–151.

Naghdy, F., Vial, P., and Taylor, N. 2003. Embedded Internet laboratory. *Int. J. Electrical Eng. Education 19*, 3, 427–432.

NASH, E. B., EDWARDS, G. W., THOMPSON, J. A., AND BARFIELD, W. 2000. A review of presence and performance in virtual environments. *Int. J. Hum. Comput Interact 12*, 1, 1–41.

NEDIC, Z., MACHOTKA, J., AND NAFALSKI, A. 2003. Remote laboratories versus virtual and real laboratories. In *Proceedings of the 2003 33rd Annual Frontiers in Education Conference*. Boulder, CO. T3E.1-T3E.6.

NERSESSIAN, N. J. 1991. Conceptual change in science and in science education. In *History, Philosophy, and Science Teaching*, M. R. Matthews, Ed. OISE Press, Toronto, Canada, 133–148.

NEWBY, M. 2002. An empirical study comparing the learning environments of open and closed computer laboratories. *J. Inf. Syst. Education 13*, 4, 303–314.

NOEL, R. W. AND HUNTER, C. M. 2000. Mapping the physical world to psychological reality: Creating synthetic environments. In *Proceedings of the Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*. New York. 203–207.

NUNEZ, D. AND BLAKE, E. 2003. Conceptual priming as a determinant of presence in virtual environments. In *Proceedings of the 2nd International Conference on Computer Graphics, Virtual Reality, Visualization and Interaction in Africa*. Cape Town, South Africa. 101–108.

OEHMKE, R. L. T. AND WEPFER, W. J. 1985. Microcomputers in the undergraduate instrumentation lab. In *Proceedings of the ASME Computers in Engineering 1985 Conference*. Boston, MA. 159–165.

OGOT, M., ELLIOTT, G., AND GLUMAC, N. 2003. An assessment of in-person and remotely operated laboratories. *J. Eng. Education 92*, 1, 57–62.

PAPATHANASSIOU, A., OSTER, J., AND BAIER, P. W. 1999. A novel simulation concept of reduced computational cost for TD-CDMA mobile radio systems with adaptive antennas. In *Proceedings of the Vehicular Technology Conference (VTC 1999), Fall.* Amsterdam, the Netherlands. 218–222.

PARUSH, A., HAMM, H. AND SHTUB, A. 2002. Learning histories in simulation-based teaching: The effects on self-learning and transfer. *Comput. and Education 39*, 319–332.

PATRICK, J. 1992. *Training: Research and Practice*. Academic Press, San Diego, CA.

PHILIPPATOS, G. C. AND MOSCATO, D. R. 1971. Effects of constrained information on player decisions in experimental business simulation: Some empirical evidence. *J. ACM 18*, 1, 94–104.

PEA, R. D. 1993. Learning scientific concepts through material and social activities: Conversational analysis meets conceptual change. *Educational Psychologist 28*, 3, 265–277.

PEA, R. D. 1994. Seeing what we build together: Distributed multimedia learning environments for transformative communications. *J. Learning Sci. 3*, 3, 283–298.

PEA, R. D. 2002. Learning science through collaborative visualization over the internet. In *Proceedings of the Nobel Symposium (NS 120)*. Stockholm, Sweden. 1–13.

PSILLOS, D. AND NIEDDERER, H. 2002. Issues and questions regarding the effectiveness of labwork. In *Teaching and Learning in the Science Laboratory*, D. Psillos and H. Niedderer, Eds. Kluwer Academic, 21–30.

RAINERI, D. 2001. Virtual laboratories enhance traditional undergraduate biology laboratories. *Biochemistry and Molecular Biology Education 29*, 4, 160–162.

REINER, M. AND GILBERT, J. 2000. Epistemological resources for thought experimentation in science learning. *Int. J. Sci. Education 22*, 5, 489–506.

RIFFELL, S. AND SIBLEY, D. 2004. Using web-based instruction to improve large undergraduate biology courses: An evaluation of a hybrid course format. *Comput. and Education 44*, 3, 217–235.

RICE, S. L. 1975. Objectives for engineering laboratory instruction. *Eng. Education 65*, 285–288.

ROHRIG, C. AND JOCHHEIM, A. 1999. The virtual lab for controlling real experiments via Internet. In *Proceedings of the 1999 IEEE International Symposium on Computer Aided Control System Design*. Kohala Coast Island of Hawaii, Hawaii. 279–284.

ROHRIG, C. AND JOCHHEIM, A. 2001. Group-Based learning using a remote laboratory. In *Proceedings of the 2001 American Control Conference*. 1153–1154.

ROSS, R. J., BORONI, C. M., GOOSEY, F. W., GRINDER, M., AND WISSENBACH, P. 1997. Weblab! A universal and interactive teaching, learning, and laboratory environment for the world wide web. In *Proceedings of the 28th SIGCSE Technical Symposium on Computer Science Education*. San Jose, CA. 199–203.

ROTH, W. M., MCROBBIE, C. J., LUCAS, K. B., AND BOUTONNE, S. 1997. The local production of order in traditional science laboratories: A phenomenological analysis. *Learning and Instruction 7*, 2, 107–136.

SAKIS MELIOPOULOS, A. P. AND COKKINIDES, G. J. 2000. Role of laboratory education in power engineering: Is the virtual laboratory feasible? III. Virtual power system laboratories: Is the technology ready. In *Proceedings of the 2000 IEEE Power Engineering Society Summer Meeting*. 1484–1489.

SALTSBURG, H., HEIST, R. H., AND OLSEN, T. 1982. Microcomputers in a college teaching laboratory-Part I. *Micro 53*, 53–55.

SCANLON, E., COLWELL, C., COOPER, M., AND PAOLO, T. D. 2004. Remote experiments, reversioning and rethinking science learning. *Comput. and Education 43*, 1–2, 153–163.

SCANLON, E., MORRIS, E., DI PAOLO, T., AND COOPER, M. 2002. Contemporary approaches to learning science: Technologically-mediated practical work. *Studies in Sci. Education 38*, 73–114.

SCHAUBLE, L., GLASER, R., DUSCHL, R. A., SCHULZE, S., AND JOHN, J. 1995. Students' understanding of the objectives and procedures of experimentation in the science classroom. *J. Learning Sci. 4*, 2, 131–166.

SCHWAB, J. 1964. Structure of the disciplines: Meanings and significances. In *The Structure of Knowledge and the Curriculum*, G. W. Ford and L. Pugno, Eds. Rand McNally and Company, Chicago, 6–30.

SCHWARTZ, T. L. AND DUNKIN, B. M. 2000. Facilitating interdisciplinary hands-on learning using LabView. *Int. J. Eng. Education 16*, 3, 218–227

SEHATI, S. 2000. Re-engineering the practical laboratory session. *Int. J. Electrical Eng. Education 37*, 1, 86–94.

SELVADURAY, G. 1995. Undergraduate engineering ceramics laboratory development. *Int. J. Eng. Education 11*, 4–5, 374–379.

SHAHEEN, M., LOPARO, K. A., AND BUCHNER, M. R. 1998. Remote laboratory experimentation. In *Proceedings of the 1998 American Control Conference*. Philadelphia, PA. 1326–1329.

SHEN, H., XU, Z., DALAGER, B., KRISTIANSEN, V., STROM, O., SHUR, M. S., FJELDLY, T. A., LU, J.-Q., AND YTTERDAL, T. 1999. Conducting laboratory experiments over the Internet. *IEEE Trans. Education 42*, 3, 180–185.

SHERIDAN, T. B. 1992. Musings on telepresence and virtual presence. *Presence: Teleoper. Virtual Environ. 1*, 120–125.

SHERIDAN, T. B. 1999. Descartes, Heidegger, Gibson, and God: Towards an eclectic ontology of presence. *Presence: Teleoper. Virtual Environ. 8*, 5, 551–559.

SHIN, D., YOON, E. S., LEE, K. Y., AND LEE, E. S. 2002. A web-based, interactive virtual laboratory system for unit operations and process systems engineering education: Issues, design and implementation. *Computers and Chemical Eng. 26*, 2, 319–330.

SHORT, J., WILLIAMS, E., AND CHRISTIE, B. 1976. *The Social Psychology of Telecommunications*. John Wiley and Sons, London.

SICKER, D. C., LOOKABAUGH, T., SANTOS, J., AND BARNES, F. 2005. Assessing the effectiveness of remote networking laboratories. In *Proceedings of the 35th ASEE/IEEE Frontiers in Education Conference*. Boulder, CO. 7–12.

SLATER, M. AND USOH, M. 1993. Presence in immersive virtual environments. In *Proceedings of the IEEE Virtual Reality Annual International Symposium*. Seattle, WA. 90–96.

SMITH, P. R. AND POLLARD, D. 1986. The role of computer simulations in engineering education. *Comput. and Education 10*, 3, 335–340.

SNOW, M. P. 1996. Charting presence in virtual environments and its effects on performance. Unpublished PhD. dissertation, Virginia Polytechnic Institute and State University.

SONNENWALD, D. H., WHITTON, M. C., AND MAGLAUGHLIN, K. L. 2003. Evaluating a scientific collaboratory: Results of a controlled experiment. *ACM Trans. Comput. Hum. Interact 10*, 2, 150–176.

STADEN, J. C. V., BRAUN, M. W. H., AND TONDER, B. J. E. V. 1987. Computerized pendulum experiment for the introductory physics laboratory. *Comput. and Education 11*, 4, 281–292.

STRIEGEL, A. 2001. Distance education and its impact on computer engineering laboratories. In *Proceedings of the 2001 31st Annual Frontiers in Education Conference*. Reno, NV. F2D.4–F2D.9.

SUBRAMANIAN, R. AND MARSIC, I. 2001. ViBE: Virtual biology experiments. In *Proceedings of the 10th International World Wide Web Conference*. Hong Kong. 316–325.

TAN, K. K., LEE, T. H., AND LEU, F. M. 2000. Development of a distant laboratory using labVIEW. *Int. J. Eng. Education 16*, 3, 273–282.

TAPPER, J. 1999. Topics and manner of talk in undergraduate practical laboratories. *Int. J. Sci. Education 21*, 4, 447–464.

THAKKAR, U., CARRAGHER, B., CARROLL, L., CONWAY, C., GROSSER, B., KISSEBERTH, N., POTTER, C., ROBINSON, S., SINN-HANLON, J., STONE, D., AND WEBER, D. 2000. Formative evaluation of bugscope: A sustainable world wide laboratory for K-12. Retrieved 07-1900 from Http://www.itg.uiuc.edu/publications/techreports/00-008/.

TORRES, K., LOKER, D., AND WEISSBACH, R. 2001. Introducing 9–12 grade students to electrical engineering technology through hands-on laboratory experiences. In *Proceedings of the 2001 31st Annual Frontiers in Education Conference*. Reno, NV. F2E.12-F2E.16.

TUCKMAN, B. W. 2002. Evaluating ADAPT: A hybrid instructional model combining web-based and classroom components. *Compute. and Education 39*, 3, 261–269.

TUMA, T., BRATKOVIC, F., FAJFAR, I., AND PUHAN, J. 1998. A microcontroller laboratory for electrical engineering. *Int. J. Eng. Education 14*, 4, 289–293.

TZENG, H.-W. 2001. The design of pedagogical agent for distance virtual experiment. In *Proceedings of the 2001 31st Annual Frontiers in Education Conference*. Reno, NV. F1F.18-F1F.23.

VAIDYANATHAN, R. AND ROCHFORD, L. 1998. An exploratory investigation of computer simulations, student preferences, and performance. *J. Education Business 73*, 3, 144–149.

VIAL, P. J. AND DOULAI, P. 2003. Using embedded Internet devices in an Internet engineering laboratory set-up. *Int. J. Electrical Eng. Education 19*, 3, 441–444.

VUORELA, M. AND NUMMENMAA, L. 2004. How undergraduate students meet a new learning environment? *Comput. Hum. Behavior 20*, 6, 763–777.

WATT, J. H., WALTHER, J. B., AND NOWAK, K. L. 2002. Asynchronous videoconferencing: A hybrid communication prototype. In *Proceedings of the 35th Hawaii International Conference on System Sciences*. Big Island, Hawaii. 1–9.

WEICK, K. E. 1996. Sensemaking in organizations. Sage, Newbury Park, CA.

WENTZ, W. H. AND SNYDER, M. H. 1974. Teaching research in an undergraduate laboratory. *Eng. Education 65*, 247–250.

WHITELEY, T. R. AND FARIA, A. J. 1989. A study of the relationship between student final exam performance and simulation game participation. *Simul. Games 21*, 1, 44–64.

WICKER, R. B. AND LOYA, H. I. 2000. A vision-based experiment for mechanical engineering laboratory courses. *Int. J. Eng. Education 16*, 3, 193–201.

WINER, L. R., CHOMIENNE, M., AND VAZQUEZ-ABAD, J. 2000. A distributed collaborative science learning laboratory on the Internet. *American J. Distance Education 14*, 1.

WITMER, B. AND SINGER, M. J. 1998. Measuring presence in virtual environments: A presence questionnaire. Presence: Teleoper. Virtual Environ. 7, 3, 225–240.

YOO, S. AND HOVIS, S. 2004. Technical symposium on computer science education. In *Proceedings of the 35th SIGCSE Technical Symposium on Computer Science Education*. New York, NY. 311–314.

YOUNGBLUT, C. AND HUIE, O. 2003. The relationship between presence and performance in virtual environments: Results of a VERTS study. In *Proceedings of the IEEE Virtual Reality 2003 Conference*. Los Angeles, CA. 277–278.

ZELTZER, D. 1992. Autonomy, interaction and presence. *Presence: Teleoper. Virtual Environ. 1*, 1, 127–132.

ZIMMERLI, S., STEINEMANN, M.-A., AND BRAUN, T. 2003. Educational environments: Resource management portal for laboratories using real devices on the Internet. *ACM SIGCOMM Comput. Commun. Review 53*, 3, 145–151.

ZYWNO, M. S. AND KENNEDY, D. C. 2000. Integrating the Internet, multimedia components, and hands-on experimentation into problem-based control education. In *Proceedings of the 2000 30th Annual Frontiers in Education Conference*. Kansas City, MO. T2D.5–T2D.10.

Received September 2004; revised November 2005; accepted March 2006