Effects of Laboratory Access Modes Upon Learning Outcomes

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***Abstract*—The Web was first used as a telecontrol medium in 1994. In recent times, Web-based telecontrol is being used as an educational option, providing students with remote access to laboratory hardware. The literature reporting the initial studies into telelaboratories speaks of encouraging responses from students, but very little literature actually addresses the quality of learning outcomes from this alternative access mode. A recent comparative study at the Department of Mechanical and Manufacturing Engineering at the University of Melbourne, Melbourne, Australia, randomly allocated a cohort of third-year students to one of three separate access modes—proximal, Web-based remote, or simulation—to perform the same laboratory class. A range of tools were used to measure the students' learning outcomes and their perceptions of the class. Statistically significant differences were found between the groups in their learning outcomes, students' perceptions of the laboratory class, and the ways in which they engage the learning experience.**

***Index Terms*—Comparative evaluation, learning outcomes, remote laboratories, student perceptions, virtual laboratories.**

I. Introduction

SINCE 1994 [1], telecontrol has been an increasingly viable control option. It is being applied more and more in the educational context. Web-based laboratories have been offered by universities in undergraduate engineering courses since 1996 [2], with the number and sophistication of these efforts growing each year [3].

A number of good motivations exist for providing students with remote access to laboratory hardware. The opportunity to provide laboratory classes, where otherwise impossible, and the ability to offer flexibility in the time and place in which laboratories are conducted are both powerful motivations for the field.

A less commonly explored, but equally powerful, motivation is that of quality of outcomes. The primary drive to this point has been the use of remote laboratories as an alternative mechanism for achieving the same outcomes, but little research has been enacted into whether the remote access modality may, in fact, enhance certain learning outcomes. Whether or not it does is the primary focus of the work reported in this paper.

II. Background

Laboratory classes are widely accepted as a crucial part of an undergraduate engineering degree. Good pedagogical reasons, such as illustrating and validating analytical concepts, introducing students to professional practice and to the uncertainties involved in nonideal situations, developing skills with instrumentation, and developing social and teamwork skills in a technical environment [4], [5], illustrate the need for their inclusions in undergraduate curricula.

The traditional undergraduate laboratory class is comprised of a small group of students and a demonstrator, grouped around a piece of hardware located in a laboratory. The students conduct a series of experimental procedures as outlined in the laboratory handout, record the data from the hardware, and write up a report based on these data and the underlying theory in the week or two subsequent to the session.

This traditional, proximal model is coming under increasing pressure because of the changing demands of engineering courses. Scheduling increasingly large numbers of small groups of students, each of which requires an hour (or more) of continuous and adequately supervised access to an expensive piece of laboratory equipment, is a difficult and expensive task. An increasingly prevalent solution to this dilemma is the use of alternative access modes—either simulation (or virtual) laboratories or remote access to laboratory hardware.

A. Current Trends in Remote Laboratories

Web-based access to course materials is becoming increasingly prevalent in undergraduate teaching, and numerous subsequent projects offer remote access to hardware. Both the number of remote laboratories in operation and the range of disciplines being taught continue to grow. Examples include determination of the speed of light from the resonant behavior of an inductive–capacitive circuit [6], use of a transmission electron microscope [7], and control of an inverted pendulum [8].

Collaborations between universities are becoming increasingly common. An early instance of this collaboration is the Automated Internet Measurement Lab (AIM-Lab) of the Rensselaer Polytechnic Institute, Troy, NY, and the Norwegian University of Science and Technology, Trondheim, Norway, offering nine laboratory experiments for the characterization of complementary metal–oxide–semiconductor (CMOS) devices [9]. A larger example of interuniversity collaboration is the German LearNet initiative, which comprises a consortium of eight German universities sharing remote laboratories with each other [10].

The field of telelaboratories has matured to the point that there have been publications providing a summary of remote laboratories throughout the world, such as [11] and [3]. These summary papers give a good overview of the range of remote laboratories in existence.

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B. "Hands-On" or Remote Laboratories?

Despite the increased prevalence of remote laboratories, a common view is that they are inferior to proximal laboratories—indeed, the first ever remote laboratory made (without supporting evidence) states that " 'hands-on' laboratory experience remains the best way to educate students. . .."

One obvious difference in a purely technology-mediated laboratory class will be the absence of the haptic experience—a topic emphasized by Tuttas in his experimental design [12]. This hands-on experience is important, but significant cognitive aspects are involved as well, and little has been done to determine how these cognitive outcomes are affected.

C. Constructivist Theory

Constructivist theory explains that the different experiences encountered in proximal or remote access to laboratories should lead to different learning outcomes. People learn through assimilating new experiences into their previous experiences, and in this way, they construct their own reality—new knowledge is anchored by previous knowledge [13]. Changing the context in which the students encounter the material potentially changes the anchors that are used to assimilate the information, with different aspects of the laboratory experience being emphasized differently. Students who encounter hardware in a dark, hot, and noisy laboratory will have different memories from students who encounter the same hardware remotely from a well-lit, air-conditioned computer laboratory. This change in context may affect the way in which the information is assimilated, based on different memory triggers.

The nature of the feedback received is also important. In a proximal laboratory, the students engage directly with the piece of hardware that they see. Although their interactions with the hardware—measurements, control signals, etc.—may be technology mediated, the students are still able to inspect the hardware itself without this mediation. In a remote laboratory, all of the students' interactions are moderated through the technology, including the processes by which they establish their understanding of the hardware.

Another critical factor is the students' mental perception of the hardware. Students will potentially engage quite differently with a piece of hardware located directly in front of them than with a piece of hardware that is located in a different room, building, or city. This cognitive engagement on the part of the students can also substantially alter the nature of their learning experience.

The different access modes do represent different experiences for the students and, as such, potentially lead to different learning outcomes.

D. Evaluation of Remote Laboratories

In spite of the increased volume of literature on the feasibility of remote laboratories and because comprehensive studies into the evaluation of these laboratory classes have not taken place, "unanswered is the question on the effects of learning outcomes" [12]. This absence of proper evaluation is demonstrated by its absence even from the summary papers concerning the field. Trevelyan [3] refers to a preliminary publication arising from the present research [14] as "an unusual experiment" dealing with evaluation of outcomes. No other references to studies involving evaluation of outcomes were made. The majority of the literature in the field is published as feasibility studies, showing that the chosen experiment is technically feasible in a remote mode. A few of the papers show preliminary intentions of how evaluation will be done (e.g., [12]), but on the whole a paucity of concrete evaluation of actual outcomes exists.

Some outcomes are clearly agreed upon within the literature. An increase in motivation and enthusiasm among students is almost unanimously reported, and the benefits of potential access to a greater variety of more sophisticated hardware are also lauded.

Another phenomenon that appears to be universally accepted within the literature is that the interface has an impact upon the outcome. The most commonly reported drawback of remote laboratory systems is a lack of transparency in the interface—rather than being merely the vehicle for interaction with the remote hardware, the interface itself becomes a focus of attention for the students.

The use of technology simultaneously introduces two competing effects—an amplification effect and an attenuation effect [15]. The amplification effect is the net positive effect of the introduction of the technology and can come from many sources. Automation of tedious tasks, faster calculations, and improved data management are all examples of these kinds of amplification effects. The attenuation effect is the net negative effect introduced by the technology. It often results from the "opacity" of the technology—the extent to which the user focuses upon the technology itself, rather than upon the material the technology is to support.

Lack of clarity of feedback is a common mistake, with students unable to be sure which commands are being executed at which time—such as in the T3 Telelaboratory, a 1997 study involving a group of nine English, mature-age students controlling a Lego train located in Finland [16].

Time delays are also a commonly reported drawback, such as those reported in [17], where a questionnaire applied to students identified response time and documentation/help info as the two main areas needing improvement—both of which are areas dealing with the transparency of the interface.

The deficiency in these findings is that the vast majority of the evaluation that has actually been performed has been based upon either anecdotal evidence or upon student surveys. One of the fundamental problems of student feedback is the potential for dissonance between the students' perceptions of their learning and the reality of their learning. Students may be able at a broad level to determine their own learning progress, but this accomplishment does not extend to the capacity to evaluate adequately alternative access modes.

Although encouraging, and a positive result, *per se*, positive student feedback does not necessarily correlate to improved, or even equivalent, learning outcomes. One should note, however, that students' perceptions are worthy of investigation. Certainly, students who enjoy a course may have improved motivation and attention, which may lead to improved educational outcomes [18]. A more positive attitude toward a course and its content is also an improvement that facilitates retention of students and promotion of the course to others. The concern is that students' perceptions are often confused with the reality of their learning experience. Simply because a student believes he or she has learned better does not make the learning so, nor does the opposite apply. While there may be correlations, the actual outcomes must be systematically measured, rather than simply assuming that the two match.

E. One Comparative Study

There has been one study reported that attempts to handle the learning outcomes in a systematic fashion [19]. In this study, a laboratory class in fluid mechanics was provided in the remote access mode and in a control group using the proximal mode. Students were randomly allocated to one of the two access modes. No attempt was made to ensure the homogeneity of the groups. The remote group was further separated into two subgroups, with one group given an hour in the laboratory to go through the prelaboratory exercises, and the other only coming to the laboratory to conduct the experiment. The groups were compared using two evaluation instruments—the overall marks the students received for their laboratory work and a survey completed by the students.

The study found that there was no significant difference between the average marks for the remote-mode group and the proximal-mode group. Significant differences resulted between the remote subgroups that did and did not have an hour's access to do the prelaboratory, with those having access performing better. Feedback surveys from the students showed that the students in the proximal group were more concerned about making mistakes when running the equipment but that little difference existed in their perceptions of the accuracy of the data.

Although a positive attempt at evaluation took place, the study was subject to several confounding factors. Primary among these is the effect of aggregation. The reports overall were graded out of a total of 150 points, aggregating a total of seven different sections, each of which contained a number of expected outcomes. This aggregation process removes the distinction as to which outcomes are being enhanced or degraded and prevents the investigators from being able to detect specific changes in outcomes. This study does not determine whether there is no change, or whether, in fact, two (or more) changes serve to cancel each other's effects on the overall mark.

Another potentially confounding factor is the issue of laboratory supervision. Only the proximal mode was supervised, with students in the remote mode completing the laboratory class without the presence and supervision of a laboratory demonstrator. The presence of an expert mentor is critical in the area of learning by doing [20], and the change from supervised to unsupervised learning will have a substantial effect upon the learning experience above and beyond that of changing access mode. One of the advantages of remote access laboratories is the opportunity for independent, asynchronous access to hardware—access that would be largely unsupervised. The impact of moving from a supervised group laboratory to an unsupervised individual laboratory is thus of considerable interest, but the net impact of two effects is not emphasized in [22]. By contrast, the focus of the present paper is the impact of the access mode itself, without any confounding factors involved.

F. In Summary

The focus of the majority of the literature on telelaboratories is on the mechanics of providing remote access or a demonstration of its feasibility. In general, evaluation of the educational effectiveness has received scant attention. Studies that do report outcomes are confounded by comparisons between individual work and group work, between supervised and unsupervised work, between the students' perceptions and their reality, and by the lack of a control group. The present paper outlines a study in which these confounding factors have been addressed and a comprehensive evaluation undertaken.

III. The Laboratory Class

The laboratory that was investigated in this instance was the calibration of a piezoelectric accelerometer. This class forms a practical component for a third-year Mechanical Engineering unit in Data Acquisition and Control. This unit is common to many degree programs within the department and is taught to a combined cohort drawn from these programs. Although administratively the students are considered to be completing different courses for their different degrees, in practice they attend the same lectures and the same laboratory class, and no distinction is made between them in the teaching process.

A. The Hardware

In this laboratory experiment, the accelerometer is mounted on an electrodynamic shaker, which is excited using signals generated by a spectrum analyzer. The velocity of the accelerometer is also measured by a laser Doppler vibrometer. This velocity signal, and the accelerometer's own acceleration measurement, are analyzed using the spectrum analyzer. The hardware is shown in Figs. 1 and 2.

The spectrum analyzer compares the voltages produced by the accelerometer circuit and the laser Doppler circuit using the frequency response $H(\omega)$, which is defined as

$$H(\omega) = \frac{\mathrm{V}_{\mathrm{ACCELEROMETER}}}{\mathrm{V}_{\mathrm{LASER\ DOPPLER}}}.$$

The theory of the experiment suggests that the relationship between the magnitude of $H(\omega)$ and the operating frequency ω will be a straight line: $H(\omega) = B\omega$, with B being a constant related to the calibration constant of the accelerometer. In reality, however, the dynamics of the test equipment make the relationship more complicated, as shown by the experimental measurement in Fig. 3.

This laboratory is conducted primarily through a single point of control—the spectrum analyzer. As a result, the alternative access modes are simply a matter of providing a remote mechanism for controlling the spectrum analyzer, achieved in the remote implementation using a general-purpose interface bus (GPIB) connection.

A MATLAB graphical user interface (GUI), shown in Fig. 4, was constructed to represent the spectrum analyzer, shown in Fig. 5, and to provide the user with access to the function-

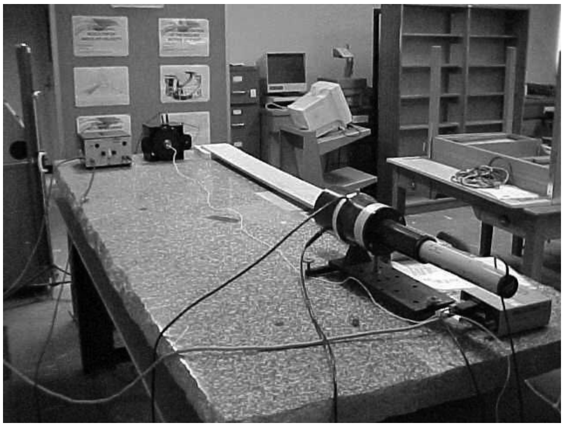


Fig. 1. Laboratory hardware.

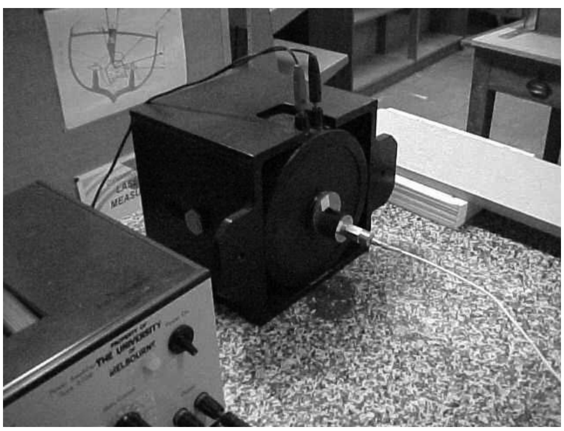


Fig. 2. Accelerometer mounted on the electrodynamic shaker.

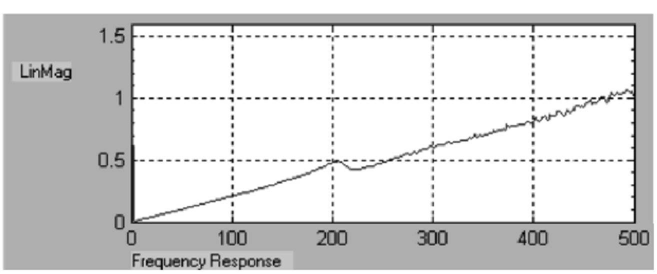


Fig. 3. Experimental frequency response.

ality of the spectrum analyzer that was necessary to perform this experiment.

A simulation of the system was also constructed, using the same GUI as the remote interface. This simulation used recorded data from the system to generate responses interactively for the user. The simulation access mode differed from the remote mode only in the students' belief of whether there was actually real hardware involved. All other factors were kept the same. In this way, some insight into the importance of the students' awareness of the access mode could be gained.

B. The Cohort

The cohort for this laboratory class comprised 146 third-year students in the Department of Mechanical Engineering. The students were drawn from a number of degree programs, including Mechanical, Mechatronic, and Environmental Engineering. The cohort included single- and combined-degree students. The students had all completed a prerequisite course in linear feedback control (almost all in the semester prior to this course).

Demographic data was also collected for each student to ensure that no external factors were confounding the outcomes. Seven factors were considered—age, gender, the course the student was taking, the student's degree program, English- or non-English-speaking background, local or overseas-based student, and full-time or part-time student. Analysis of these demographic data showed minimal bias in the makeup of the groups allocated to each access mode.

Not all of the 146 students involved in the study provided an equivalent amount of data to the study—some did not complete the post-test; some did not submit their assignments. A number of the reports that were submitted were found to involve plagiarism of some kind and were excluded from the quantitative analysis of outcomes. A total of 118 students were considered in the quantitative analysis of this trial, with the remainder being excluded because of the absence of some information. Analysis of post-test information, however, had far fewer exclusions, with 139 of the 146 students represented.

IV. The Evaluation Tools

A. Assignment Marking

The students each submitted a written report on their laboratory class, due two weeks after the completion of the laboratory. The reports were marked according to whether specific behaviors were represented. From these behaviors, 11 criteria marks were determined; and from these 11 criteria marks, measures of eight learning outcomes were constructed. The interaction among the behaviors, criteria, and outcomes is illustrated in Fig. 6.

Each criterion has associated behaviors, varying from five to nine in number, depending upon the criterion. The eight outcomes are identified by letters A–H; the 11 criteria are numbered 1–11; and the behaviors within each criterion are referred to using Roman numerals. A previous publication regarding this work [21] used letters to denote behaviors, although the ordering is the same.

The student's mark for a criterion is simply the number of associated behaviors displayed in his or her report. The behaviors are not included, and where the behaviors appear in the report does not matter. For example, the behaviors for criterion 4 are as follows.

- *Criterion 4—Deviation from the "ideal" $H(\omega)$ versus ω straight-line response:* The actual response of the system will deviate from the "ideal" straight-line response assumed in the laboratory handout. The student does the following:
  - I. identifies that the response deviates from the "ideal" straight line;
  - II. observes that the gradient of the line changes with frequency;
  - III. observes that the response contains oscillation around the ideal straight-line response;
  - IV. observes that the response does not have a zero magnitude at $\omega = 0$;

Fig. 4. GUI interface.

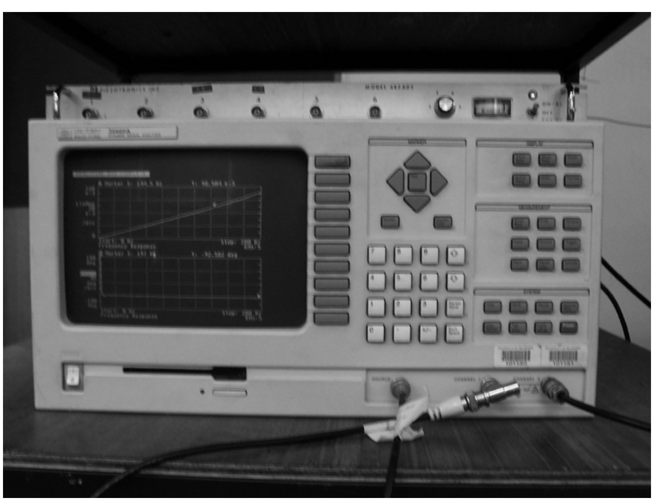


Fig. 5. Real analyzer interface.

V. provides explanations to explain this deviation;
VI. identifies that this deviation compromises the calibration of the accelerometer as a sensor.

Thus, for example, a student who indicates that the response is not a straight line, and that it does not have a zero magnitude at $\omega = 0$, but does not include any of the other behaviors, will score two for criterion 4.

This fine-grained approach to marking the reports reduced the potential confounding impact of the marker. Marking is a digital yes–no process rather than a continuous "feels like 70%" approach.

The laboratory class is intended to produce eight learning outcomes—three that are task specific and five that are generic skills usually associated with third-year engineering students, as follows:

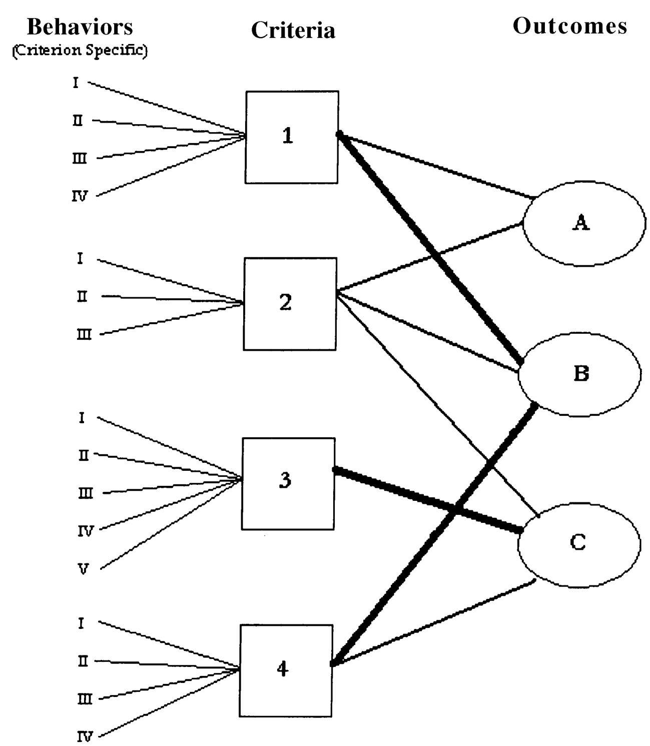


Fig. 6. Representation of the interaction between behaviors, criteria, and outcomes.

Specific Outcomes:

A) appreciation of the hardware involved;
B) reasons for calibration;
C) the complexity of signals;

Generic Skills:

D) identification of assumptions;

TABLE I
CRITERIA–OUTCOME LINKAGES

No.	Criterion	Outcomes
1	The relationship between $H(\omega)$ and ω	**F**
2	The Calibration Constant *A* (Final Value)	F,**G**
3	The Calibration Process	C,F,H
4	Deviation from the 'ideal' $H(\omega)$ vs ω straight line response	E,F
5	Assumptions involved in simplifying the transfer function	**D**
6	Linearity of the Accelerometer system	C,**H**
7	Resonance / Anti-resonance pair	**E**
8	The Piezoelectric Accelerometer	**A**
9	The laser Doppler System	**A**
10	Calibration as a process	**B**
11	Spectral Analysis	A,**C**

E) exception handling;
F) processing of data;
G) limitations of accuracy;
H) Comparison of data.

These outcomes are measured as linear combinations of the criteria marks. The links between criteria and their related outcomes are shown in Table I. The bold letters indicate strong relationships, which were weighted twice as heavily in determining the outcome score. From these relationships, values for the eight different outcomes were determined for each student.

B. Post-Test

Students also completed a seven-question post-test to gauge their perceptions of the experience. The questions were on a single A4 page, and students were asked to complete the post-test after completing the laboratory work, but prior to completing the laboratory report. The following seven questions were asked:

1) These laboratory classes are being run with three access modes—proximal (in person in the laboratory), remote, and simulation. What effect do you think your access mode had upon the laboratory class?
2) If given a free choice, which access mode would you have chosen and why?
3) Did you feel your calibration of the accelerometer was accurate?
4) What did you think the learning objectives of the laboratory class were?
5) What was the most important thing you learned from the laboratory class?
6) Did you find the laboratory class intellectually stimulating? Why or why not?
7) Do you have any other comments, positive or negative?

These are open-ended questions which lead to a wide variety of responses. There were emerging themes in the responses for most of the questions, allowing for responses to be grouped and comparisons made between these aggregated values.

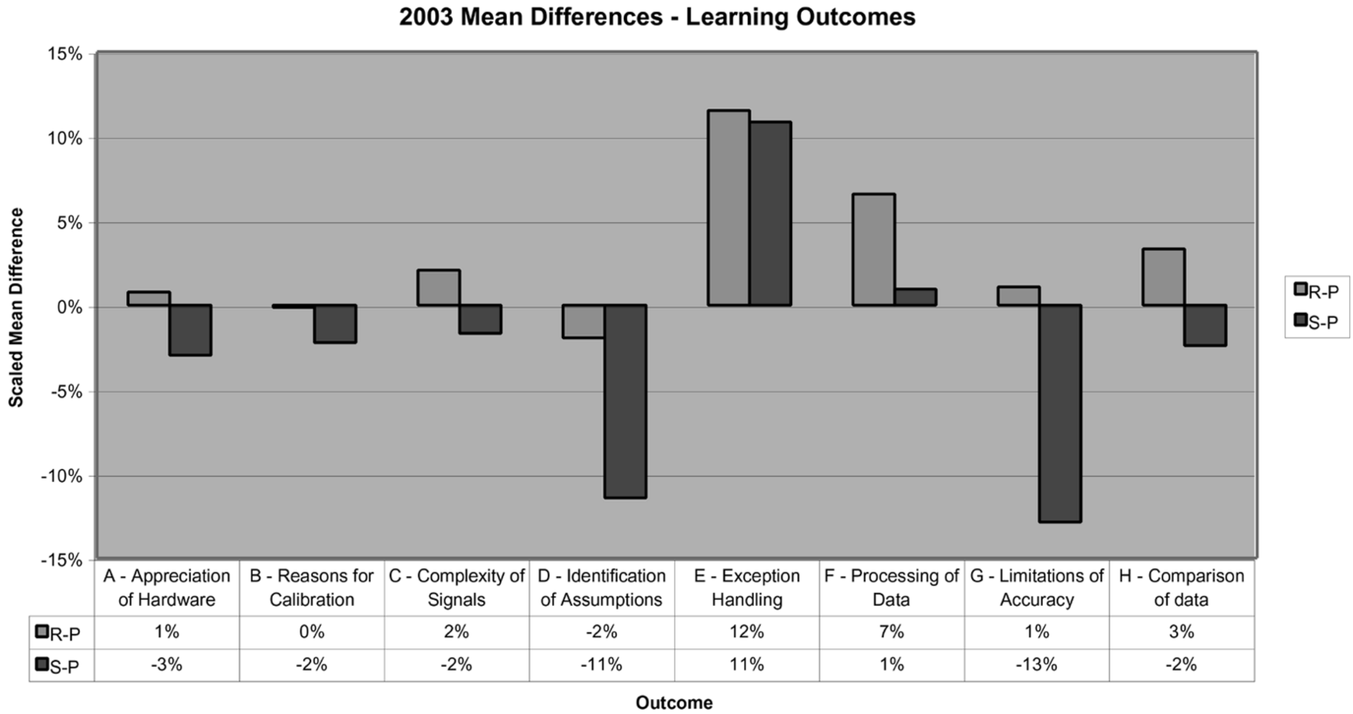
V. Finding 1: The Access Mode Affects Some Learning Outcomes

Because of the derivation of the outcomes as linear combinations of criteria, the outcomes have different scales. To allow meaningful comparisons between outcomes, the outcomes were rescaled to a percentage of the maximum value for that outcome. The scaled differences between the means for the nonproximal groups and the proximal group are shown in Fig. 7.

Pairwise analysis of differences between the means using Tukey's honestly significant difference test [22] shows that for outcome E—exception handling—there exists a highly significant $(p = 0.005)$ difference between the means of the proximal and remote groups, and a significant $(p = 0.011)$ difference between the means of the proximal and simulation groups. The proximal group is in a separate subset of its own, indicating that the proximal mode is significantly different to both other modes for this outcome.

For outcome G—limitations of accuracy—highly significant differences exist between the means of the proximal and simulation groups $(p = 0.001)$ and between the remote and simulation groups $(p < 0.001)$. The simulation group is in a separate subset of its own, indicating that the simulation mode is significantly different than both other modes for this outcome.

These results were verified against the Games–Howell [22] test to account for possible errors introduced as a result of unequal sample sizes or variances, with the same results (although slightly different p values).



	A - Appreciation of Hardware	B - Reasons for Calibration	C - Complexity of Signals	D - Identification of Assumptions	E - Exception Handling	F - Processing of Data	G - Limitations of Accuracy	H - Comparison of data
R-P	1%	0%	2%	-2%	12%	7%	1%	3%
S-P	-3%	-2%	-2%	-11%	11%	1%	-13%	-2%

Fig. 7. Differences in outcome means for remote and simulation modes relative to proximal mode.

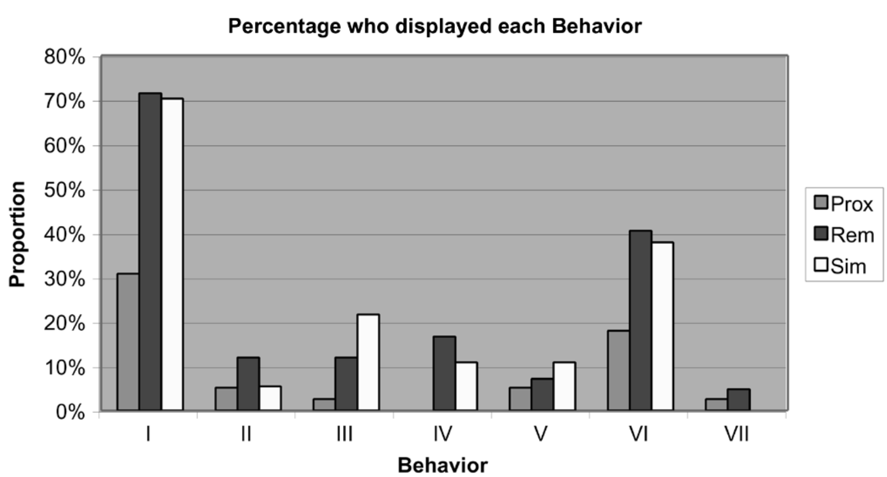


Fig. 8. Behavior analysis for Outcome E: Proportion of students in each access mode who displayed the particular behaviors contributing to the exception handling outcome.

1) Reasons for the Differences—Outcome E (Exception Handling): To determine why differences exist among the three modes, a deeper investigation of the data was performed. Outcome E is comprised of two criteria—criteria 7 and 4. The behaviors involved in criterion 7—the resonance/antiresonance pair—are as follows:

I. The student identifies the existence of the resonance and the antiresonance.
II. The student indicates that these resonances compromise the calibration he or she has just completed.
III. The student notes the range of frequencies (180–230 Hz) that are affected by the resonances.
IV. The student explains that the operating envelope for the accelerometer must not include the frequencies affected by the resonances.
V. The student indicates that these resonances will alter the gradient of the $|H(\omega)|$ versus ω curve.
VI. The student lists the possible causes of these resonances.
VII. The student postulates possible remedies to correct these causes of resonance.

The proportion of students who displayed each behavior in their reports was calculated, and the modewise distribution is displayed in Fig. 8.

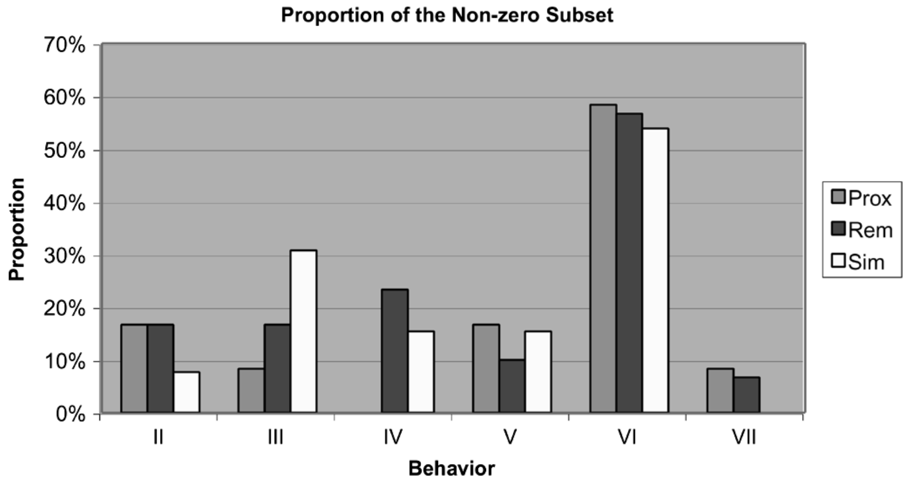


Fig. 9. Behavior analysis for Outcome E: Proportion of students in each access mode who, having recognized the resonance/antiresonance (behavior I) and then displayed the associated behaviors II–VII.

Fig. 8 shows that the most substantial difference is in behavior I—whether the students even acknowledge that these nonidealities exist. The proportion of proximal mode students that do is less than half of either of the other modes. This discovery leads to a significant increase in the number of zero marks for the outcome, and thus lowers the mean performance considerably.

Further insight can be gained by considering only those students who did display behavior I—by eliminating those who scored zero for the outcome (Fig. 9).

Fig. 9 shows that among the students who do identify the nonideality, a further difference exists between the proximal mode and other modes in the proportions displayed by behaviors III and IV—identifying the range of frequencies affected and the need to exclude these ranges from the operating envelope. This analysis shows that the students in the nonproximal modes not only are more likely to observe that these nonidealities are present, but also are more likely to understand the consequences of this presence once identified.

Criterion 4, deviation from the "ideal" $H(\omega)$ versus ω straight-line response, is also involved in determining Outcome E, and thus differences in its associated behaviors must also be considered. The student does the following:

I. identifies that the response deviates from the "ideal" straight line;
II. observes that the gradient of the line changes with frequency;
III. observes that response contains oscillation around the ideal straight-line response;
IV. observes that the response does not have a zero magnitude at $\omega = 0$;
V. provides information to explain this deviation;
VI. identifies that this deviation has a negative impact upon the linearity of the accelerometer as a sensor.

The proportion of students who displayed each behavior in their reports was calculated, and the modewise distribution is displayed in Fig. 10.

Fig. 10 shows significantly larger proportions of the remote and simulation mode that display behaviors III and IV—further indicating that the proximal mode is less proficient at detecting unanticipated results.

2) Reasons for the Differences—Outcome G (Limitations of Accuracy): Recall that for this outcome, the simulation mode performance was inferior to that in the other modes. Outcome G depends entirely upon criterion 2, and only the eight behaviors that contribute to criterion 2 will be responsible for the between-mode differences in Outcome G. The eight behaviors in question are as follows:

I. The student determines a value for the calibration constant A.
II. The student comments upon the discrepancy between the calibration value of A and the manufacturer's specified value.
III. The student determines a value for A that is within 10% of the manufacturer's specifications $(918\ \mu\text{Vs}^2/\text{m} < \text{A} < 1122\ \mu\text{Vs}^2/\text{m})$.
IV. The student determines a value for A that is within manufacturer's specifications $(1000\ \mu\text{Vs}^2/\text{m} < \text{A} < 1040\ \mu\text{Vs}^2/\text{m})$.
V. The student gives an estimate of the reliability/error tolerances of their calculated value of A and a justification of this estimate.
VI. The student gives an estimate of the reliability/error tolerances of the manufacturer's specified value of A and a justification of this estimate.
VII. The student explores potential causes of the discrepancy between their calculated A value and the manufacturer's specification.
VIII. The student offers potential solutions to these causes of this discrepancy.

The proportion of students in each access mode who displayed each behavior in their reports is displayed in Fig. 11. The simulation-mode proportions are smaller for all but one behavior.

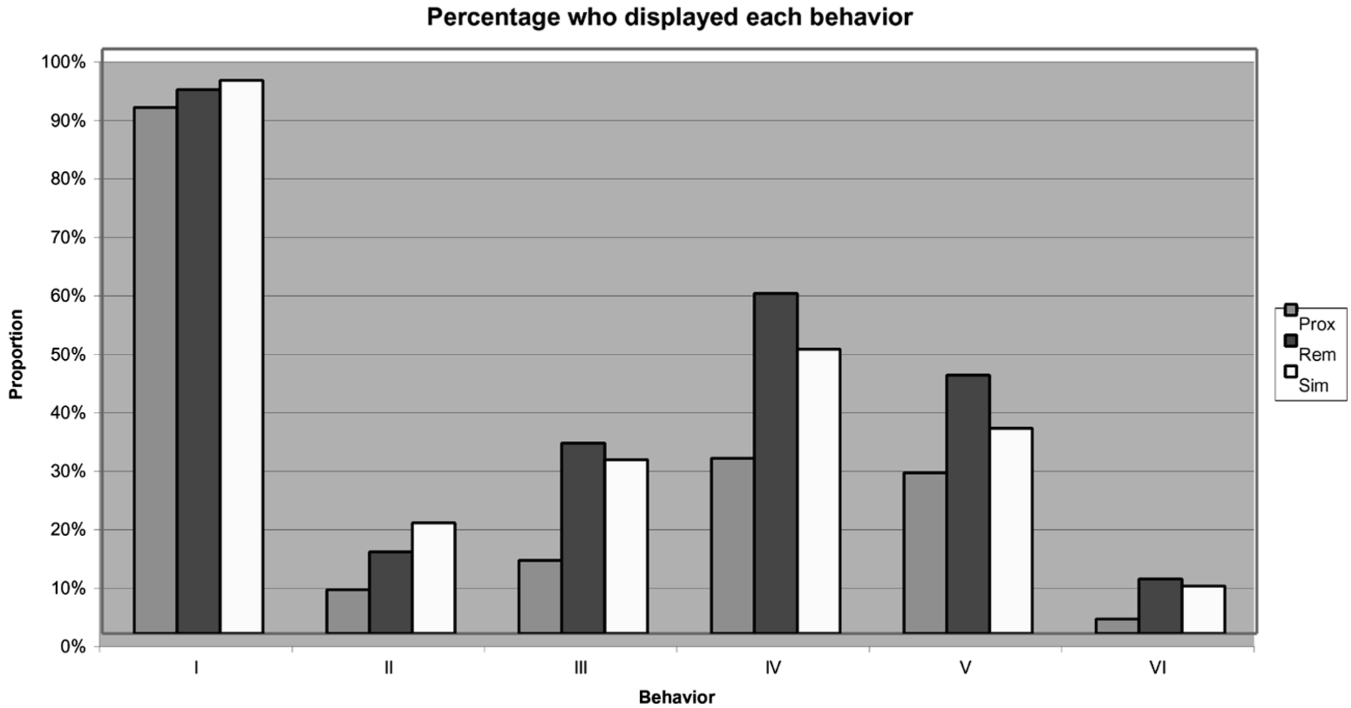


Fig. 10. Behavior analysis for Outcome E: Proportion of students in each access mode who displayed the particular behaviors contributing to criterion 4 of the exception-handling outcome.

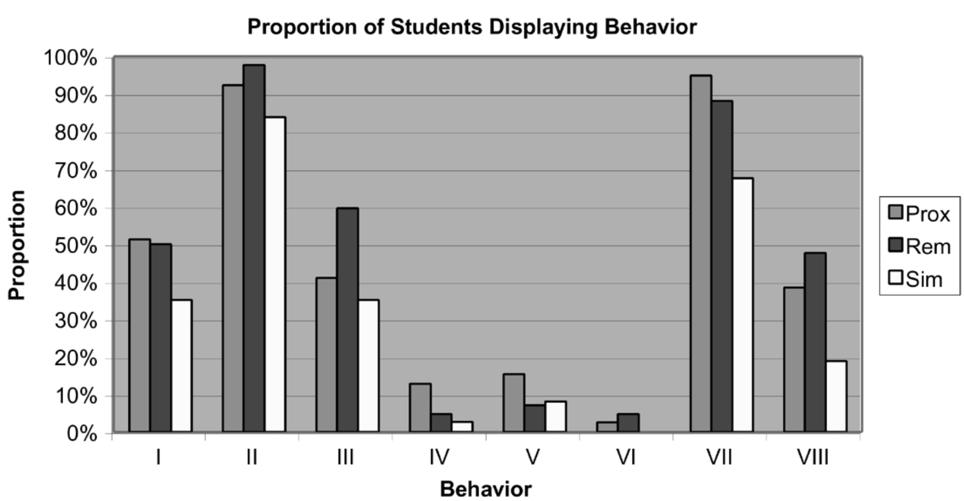


Fig. 11. Behavior analysis for Outcome G: Proportion of students in each access mode who displayed the particular behaviors contributing to the accuracy limitations outcome.

The differences between the simulation proportions and the proximal and remote proportions is shown in Fig. 12.

Fig. 12 shows that the largest differences in the proportions occur for behaviors III, VII, and VIII. Behavior III deals with the accuracy of the final answer, indicating that there were fewer arithmetic mistakes made by students in the remote mode. Behaviors VII and VIII deal with the causes of discrepancies and their potential solutions. This finding suggests that students in the simulation mode gave less thought to the significance of their calibration constant once it had been found. They did not consider why it may differ from the manufacturer's specification, nor how they might remedy these discrepancies. These results may have come from the higher degree of abstraction from the real hardware involved in the simulation mode.

VI. Finding 2: Access Mode Affects Perceptions of the Laboratory Objectives

The students' perceptions of the objectives and outcomes of the laboratory class are shown by their responses to questions 4 and 5 in the post-test survey—"What did you think the learning objectives of the laboratory class were?" and "What was the most important thing you learned from the laboratory class?"

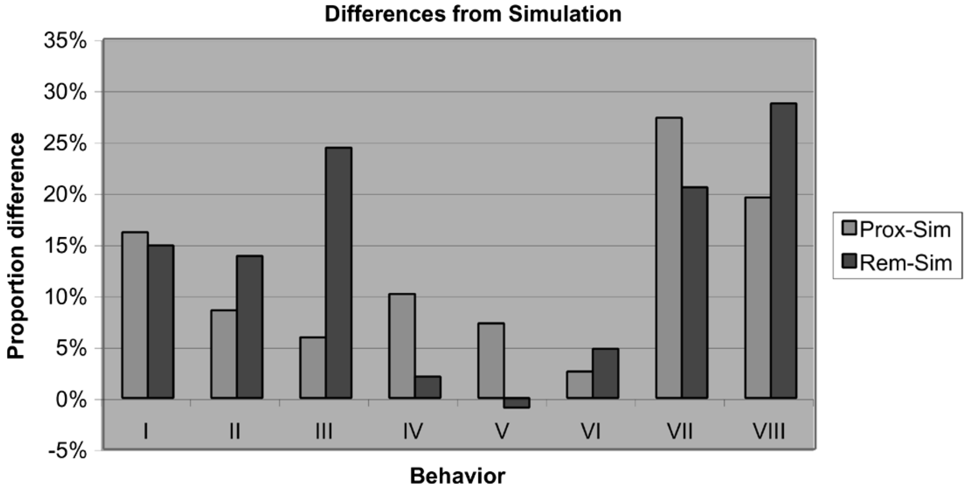


Fig. 12. Differences from simulation mode in proportions of proximal- and remote-mode students who exhibited the particular behaviors contributing to Outcome G (limitations of accuracy).

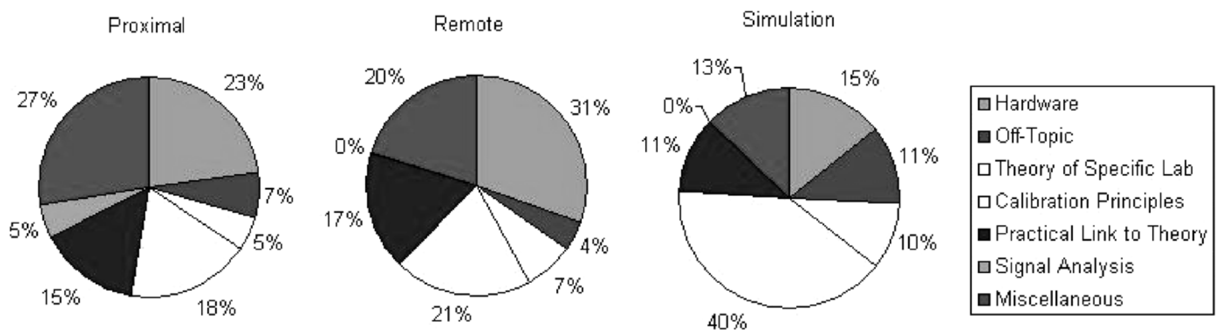


Fig. 13. Distribution of perceptions of laboratory objectives for each access mode.

The responses to these questions were grouped into seven categories, with the same categories used for both to allow for comparisons not only between modes, but also between perceived objectives and perceived outcomes.

A. Access Mode Alters Perceptions of Objectives

Substantial differences were detected in the distributions of the responses to the different categories among the three access modes (Fig. 13).

The distributions were analyzed using a 3×7 contingency table approach (such as that found in [23]). For the table, a χ^2 test statistic of 24.694 was calculated, which is greater than the critical value of 21.03 for significance at $p = 0.05$, indicating that the differences in distribution are statistically significant.

Interestingly, remote, rather than proximal, access to the laboratory hardware did not lead to a diminished perception of the importance of hardware in the laboratory objectives, nor to a large increase in the perception of theory-related objectives (laboratory-specific and calibration principles).

The simulation implementation leads to a large bias toward calibration principles in students' perceptions of the objectives. This shift in proportions—more than 20% higher than the other groups, with 40% of the responses falling into this category—shows that the simulation mode serves to change students' perceptions of the laboratory objectives significantly. A substantial reduction of the number of responses in the hardware-specific goals category suggests that the use of the simulation serves to dissociate the students from the underlying apparatus of the experiment. Correspondingly, a modest reduction is found in the proportion of students suggesting practical applications of the theory as a laboratory objective.

B. Access Mode Does Not Alter Perceptions of Outcomes

Students' perceptions of their learning outcomes did not vary substantially among the three access modes (Fig. 14).

These proportions were again analyzed using a 3×7 contingency table. Some minor, possibly indicative differences in the distributions were noted, but nothing that approached statistical significance ($\chi^2 = 6.267$ versus 21.03 required for significance at $p = 0.05$). This finding is in contrast to their perceptions of the objectives of the laboratory class, which do differ according to access mode.

C. Students' Perceptions of Objectives and Outcomes Are Mismatched

A comparison of Figs. 13 and 14 shows that for most of the answer categories, substantial differences exist in the proportions between the perceptions of the objectives and the perceptions of the actual learning outcomes. To investigate this dissonance, the responses to both questions were compared in a 2×7 contingency table, one for each mode. The results are shown in Table II.

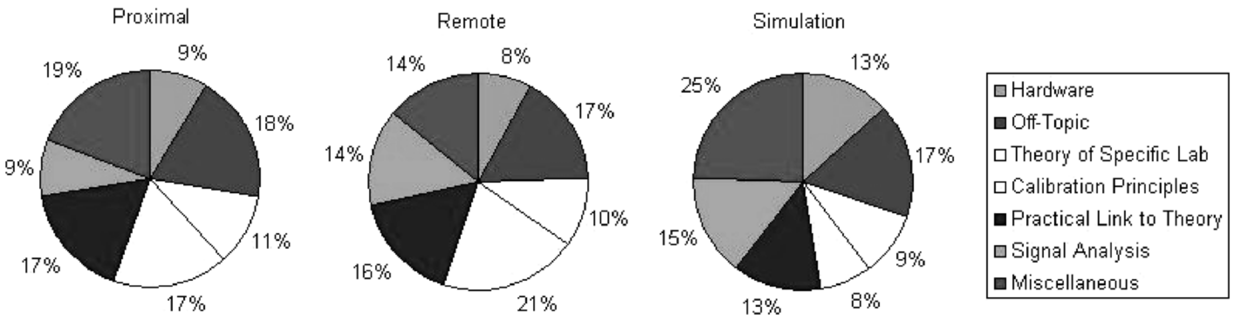


Fig. 14. Distribution of perceptions of learning outcomes for each access mode.

TABLE II
SIGNIFICANCE OF DISSONANCES BETWEEN PERCEPTIONS OF LABORATORY OBJECTIVES AND LEARNING OUTCOMES

Mode	χ^2 test statistic	P value
Proximal	9.460	> 0.10
Remote	21.870	< 0.005
Simulation	24.434	< 0.001

Table II shows that there are significant dissonances between the students' perceptions of the objectives and the outcomes for the remote and simulation modes, but not for the proximal mode. These differences can be observed in Fig. 15, which shows the differences between the proportions for the outcomes and the objectives.

1) Proximal Mode: Despite the absence of an overall significant difference for the proximal mode, significant differences were noted between the perceived objectives and outcomes for the hardware ($p < 0.03$) and the off-topic ($p < 0.03$) groupings, with the hardware emphasized in the objectives and the off-topic responses emphasized in the outcomes.

2) Remote Mode: The remote mode also displayed significant differences between the perceived objectives and outcomes for the hardware ($p < 0.002$) and the off-topic ($p < 0.02$) and signal analysis ($p < 0.001$) groupings. Hardware was again emphasized in the objectives, with the off-topic and signal analysis responses emphasized in the outcomes.

3) Simulation Mode: For the simulation mode, significant differences were found between the perceived objectives and outcomes for the calibration principles ($p < 0.0002$) and the signal analysis ($p < 0.001$) groupings. The calibration principles were substantially emphasized in the expectations, while the signal analysis group was emphasized in the outcomes.

4) Summary: The presence of the hardware appears to focus the students' attention and their expectations. Both the proximal and remote groups show a significantly larger proportion of hardware-based expectations than outcomes. In the simulation mode, where the hardware is entirely absent, no substantial difference exists between the expectations and the outcomes.

The separation from the hardware serves to promote signal analysis outcomes, while simultaneously discouraging signal analysis expectations. The signal analysis concepts deal with abstractions, such as transfer functions, rather than the tangible apparatus that is present in the proximal laboratory.

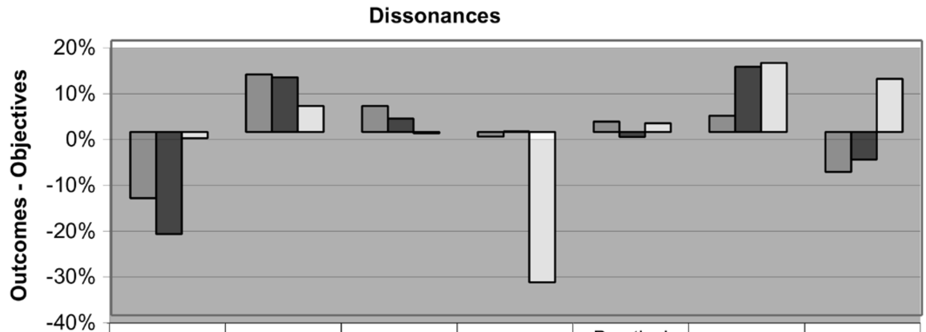
VII. FINDING 3: STUDENTS ENGAGE DIFFERENTLY IN DIFFERENT MODES

The students' engagement was measured through question 6 on the post-test survey, "Did you find the laboratory class intellectually stimulating? Why or why not?" The students' reported levels of intellectual stimulation were virtually identical across each of the three modes (with the proportion of yes answers only ranging from 85%–89% between groups), but their explanations indicated that this stimulation was a result of different aspects of the laboratory class. Students in the proximal mode seemed to focus upon novelty-based motivations, stemming from their lack of prior similar experiences. Students in the remote mode appeared to focus upon the application of theory they had learned in lectures, with the laboratory providing them an opportunity to reinforce their theoretical knowledge. Students in the simulation mode most commonly focused upon their opportunity to learn during the class, and more significantly, upon the process of learning. They valued being made to think and to answer questions. Each mode promoted engagement with a different focus of the class.

VIII. FINDING 4: STUDENTS ARE SOMEWHAT ACCEPTING OF ALTERNATIVE MODES

The students' responses to the other questions on the post-test also showed a level of acceptance of the alternative access modes, particularly among those students who had participated in a nonproximal mode.

The responses to question 1 ("What effect do you think your access mode had upon the laboratory class?") show different attitudes toward the hands-on nature of the laboratory. Students in the proximal mode felt that the absence of hands-on work would be a deficiency of the nonproximal modes, but students in the nonproximal modes did not report this absence as a concern. Students also did not report degradation in their learning outcomes, regardless of their access mode; indeed, of those that commented, all felt that their own mode had improved their learning. This acceptance was also evident in the students' responses on the matter of accuracy, with question 3, "Did you feel your calibration of the accelerometer was accurate?" Students only responded that their mode was superior in accuracy to the alternatives and never that their mode was inferior.



	Hardware	Off-Topic	Theory of Specific Lab	Calibration Principles	Practical Link to Theory	Signal Analysis	Miscell-aneous
Proximal	-14%	13%	6%	-1%	2%	4%	-9%
Remote	-22%	12%	3%	0%	-1%	14%	-6%
Simulation	-1%	6%	0%	-33%	2%	15%	12%

Fig. 15. Objectives/outcomes dissonances.

TABLE III
PREFERRED MODE (%)

Preferred Mode	Mode Experienced		
	Proximal	Remote	Simulation
Proximal	86.7	66.3	59.1
Remote	8.9	27.9	10.2
Simulation	4.4	5.8	30.7

Although the overall preference was for the proximal mode, with over two thirds of all of the responses indicating this preference, a substantial proportion of students in the nonproximal modes indicated that they preferred the mode that they had actually completed, as shown by their responses to question 2, “If given a free choice, which access mode would you have chosen and why?” (Table III).

The proportions in this table can be approximated by a 30% proportion of students who prefer the mode they experienced and a 60% proportion who prefer the proximal mode regardless of which mode they experienced. This discovery may indicate an “inertia” among the students to prefer the modes with which they are familiar—primarily the proximal mode of all of their previous laboratory classes, with a lesser block having adapted to their newer mode, but not wanting to adapt further. Alternative modes can be accepted by the students who use them.

IX. CONCLUSION

Remote laboratories are an increasingly common component of the undergraduate engineering curriculum. Initial efforts at implementing remote laboratories have focused mainly upon technical feasibility and upon the hardware and software systems that enable them. Evaluation of these experiments has concentrated on the benefits of increased flexibility in resource utilization and reports of student satisfaction, rather than quantitative investigation of the effect on learning outcomes.

In the present study, separation from physical hardware changed the students’ focus within the laboratory class. Students who experienced the nonproximal modes were more likely to identify nonidealities in the experimental results and, having identified them, were more likely to demonstrate an understanding of their consequences.

The students’ responses were not simply determined by their separation or otherwise from the hardware; in some instances, the belief that there was hardware present somewhere, even if not in the same room, lead to differences. Students involved in simulation access displayed a lesser grasp of the real context than those in the proximal group and those in the remote group, even with the remote group using an identical interface to the hardware.

The students’ perceptions of what they achieved and what they were meant to achieve were also dependent upon their access mode. Although little difference was exhibited in the students’ perceptions of their learning outcomes, significant differences existed in the perceived objectives of the class for the different access modes. The remote implementation emphasized hardware objectives in the students’ minds, while the simulation implementation emphasized theoretical objectives—another example of the simulation mode promoting a greater degree of abstraction from the hardware.

Students who had experienced the laboratory classes in modes other than the traditional, proximal, mode showed some acceptance of the alternative access mode, with one in three students indicating their new mode was their preferred mode. A substantial bias still exists toward the proximal mode, indicating some potential for these alternatives to be accepted.

Prior to this study, remote access to laboratories had been offered primarily on the basis of logistical motivations, rather than on the grounds of learning effectiveness. This study has shown that alternative access modes may improve some learning outcomes of laboratory classes, at the expense of degradation in others. The learning outcomes of the alternative access modes are different from those of the proximal experience—some for better, some for worse. For those teaching in a nonproximal mode, care must be taken to compensate for those outcomes that have been shown to be degraded in these modes. Alternatively, those looking to improve specific learning outcomes in laboratories may be better served looking to remote laboratories as a solution—a deliberate choice, rather than a convenient alternative.

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