Effects of instructional technologies on student learning in the undergraduate physics laboratory

Overview

The proposed project intends to explore undergraduate students' learning of physics using two specific instructional technologies, microcomputer-based laboratories (MBL) and digital video analysis of experimental data (also called video-based lab, or VBL). It comprises work to be done over a two-year period, based at Wittenberg University in collaboration with the Université de Montréal. It is expected that this work will lead to the development of further projects. The goal is to contribute to the growing but still insufficient knowledge available to physics educators and college decision makers on the benefits of instructional approaches that include these technologies for teaching and learning complex physics content and general science skills.

Background

Microcomputer-based laboratories have been in use for well over a decade (Tinker & Papert, 1989). They constitute a modern approach to teaching science in a learning laboratory, with students conducting experiments in which data are acquired and transmitted directly to a computer. MBLs provide the possibility of displaying graphs concurrently with the observed phenomenon, in addition to storing the data for further analysis, this latter typically performed by way of spreadsheet software. Although rooted in older applications of videodisks and videotape, the VBL approach considered here is a recent development consisting of capturing and digitizing the image of a phenomenon studied in an experiment, marking points on the digitized movie frames, and using software to analyze the data (Brungardt & Zollman, 1995; Escalada, Grabhorn, & Zollman, 1996; Zollman, 1997). Both approaches are similar, but offer a complementary potential for learning that justifies the interest in exploring the contributions of both.

There have been a number of studies published on the use of MBL, and only a few on VBL (Beichner, 1996; Berger, Lu, Belzer & Voss, 1995; Krajcik & Layman, 1993). In general, proponents of MBL mention as advantages over conventional labs the capacity to provide immediate information on the value of a variable at any given time, to display the data as a graph on the computer screen, to provide a time history of the variable under study, and to link the concrete experience of data gathering with an instantaneous symbolic representation (Adams & Shrum, 1990; Amend, Larsen & Furstenau, 1990; Friedler, Nachmias & Linn, 1990; Krajcik, 1991). Nevertheless, most of these studies were conducted with pre-college or non-science college students, and most studies examined the effects on graphing abilities: constructing, interpreting, and relating graphs to phenomena (Beichner, 1990, 1994; Brassell, 1987; Farr, 1996; Linn, Layman & Nachmias, 1987; Mokros & Tinker, 1987; Noble & Nemirovsky, 1995; Svec, 1995). Some studies have examined effects on conceptual understanding and on problem-solving (Laws, 1991a, 1991b, 1997; Lewis & Linn, 1994; Linn & Songer, 1991; Nachmias & Linn, 1987; Thornton, 1997; Thornton & Sokoloff, 1990). As for VBL, the studies mainly examined the importance of synchronization between phenomenon and graphing, as this is the feature that most significantly distinguishes this technology from MBL (Brungardt & Zollman, 1995; Escalada *et al.*, 1996).

An education in science should, however, help students to develop many other types of skills and ways of thinking besides those related to graphing. Among these are skills such as problem-solving, formulating and testing hypotheses, interpreting data, and building a deep conceptual understanding of the subject matter.

There are reasons to believe that the technology-based approaches of MBL and VBL have great potential to contribute to the development of these skills, as well as to the development of many other ones in science education (Rubin, 1993; Rubin, Bresnahan & Ducas, 1996). However, based on a first review of the literature, there appears to be very little data unequivocally supporting this claim. Thus, as a matter of educational policy, it is of great importance that more information be available for instructors, as well as decision makers, to judge the appropriate use and potential return of these approaches, which carry significant implementation costs. A better understanding of the ways in which these technologies aid learning, and how they can best be used with different types of students, is therefore desirable if MBL and VBL are to become more widely adopted and more effectively used in science teaching.

Objectives of the proposed study

Therefore, we propose a study of MBL and VBL effects on student learning of an important topic in physics: conservation of momentum and energy in interactions (collisions). To our knowledge, the effects of these technologies have not been investigated in this particular area before. (One exception is Eckstein, 1990, who describes several collision experiments using MBL, but does not discuss any learning outcomes.) The main goals of the study will be to obtain a greater understanding of what other kinds of effects (besides better graphing abilities and increased conceptual understanding of kinematics) can be expected with MBL and VBL, to directly compare MBL and VBL contributions to learning, and to provide a model for future studies on these technologies.

One perception stemming from our teaching experience, and confirmed by the literature, is that students have difficulty understanding why and when to use energy and momentum concepts to study a phenomenon rather than, for example, a kinematics or dynamics approach (Grimellini-Tomasini, Pecori-Balandi, Pacca & Villani, 1993; Lawson & McDermott, 1987). This is a significant barrier to learning, because energy is a fundamental concept in physics, necessary for understanding a wide variety of phenomena of importance to science majors and non-science majors alike. In addition, many, if not most, topics in intermediate and advanced physics courses are based on energy and momentum concepts, more so than on kinematics and Newton's Laws. The application of conservation laws to solving problems and gaining deeper understanding is also a fundamental part of learning and doing physics. These difficulties are present among students of diverse backgrounds. This problem therefore reflects a clear need to improve conceptual understanding in all students, as well as to improve procedural and strategic knowledge in technical (for example, pre-medical and engineering) and science (for example, physics and chemistry) students.

As an example of student difficulties with energy and momentum concepts, research indicates that students generally do not understand why one need not analyze the interaction occurring during collisions (Grimellini-Tomasini *et al.*, 1993). Students also have trouble deciding when and how to use energy conservation and when and how to use momentum conservation to analyze a process. A particularly good illustration of both energy and momentum conservation is the ballistic pendulum, in which a perfectly inelastic momentum-conserving collision is followed by a mechanical-energy-conserving rise of the pendulum. In working problems involving this apparatus, students must simply accept that momentum is conserved in the collision, and mechanical energy in the process of the rise of the pendulum: they do not really understand why the two conservation laws must be applied in these different places. Even when explicitly told that they need to use one conservation law for the collision and one for the rising, they often do not understand which one to use where, or why. Performing the traditional version of this experiment does not typically help them gain this insight.

There are, thus, several different but related problems. First is the understanding of the concepts of energy and momentum conservation, which is mostly declarative knowledge: do students understand these principles, and do they understand their interconnection? However, a more important question in physics education is that of correctly applying these concepts for problem-solving, the knowledge of when to use them, which is mostly strategic (or conditional) knowledge. Then, there is the question of discerning what the "system" is—that is, since one is actually computing total momentum and energy, one has to specify what one is computing it for. What is in the system and what is out of the system is a matter of choice. Why do you make certain choices? Why not include other things in the environment? Related to this is the choice of what point(s) in time to analyze: conservation means that many points can serve as "initial" and "final" states but some may be easier to analyze than others. And, of course, there is the actual modeling and computation required. All this calls for problem-solving abilities, the "how-to," which is mostly procedural knowledge.

In spite of the lack of conclusive studies to date, certain characteristics of MBL and VBL indicate their potential to contribute to students' deeper understanding and appropriate application of energy and momentum concepts and conservation laws in, for example, collision problems. First, both technologies allow for the student to concentrate on the conceptual problems involved rather than on the adjunct tasks needed in collecting and analyzing the data; in that respect, they are both examples of what has been called cognition enhancers (Dede, 1987) in the form of skillful laboratory partners. More particularly, both technologies allow for an examination of the collision period that is more direct and obvious than with traditional laboratory methods. Indeed, while a "physics view" of such phenomena calls for implicitly ignoring that precise event, it is however a reality underlined by research that students' "naive view" focuses on this event and questions the "true validity" of approaches ignoring it (Grimellini-Tomasini *et al.*, 1993; Touger, Dufresne, Gerace, Hardiman & Mestre, 1995). By being able to examine the event in detail, and by being able to look at many different examples in order to find the regularities in the phenomena, students have the opportunity to see explicitly and to come to accept the sufficiency and the efficiency, for conceptual understanding and for problem-solving, of the "physics view."

Whereas MBL offers the opportunity for students to experience a phenomenon and the corresponding graph simultaneously in real time, with VBL one generates a graph that is delayed in time from the actual viewing of the phenomenon. With VBL, however, it is possible to go step-by-step through the video clip and simultaneously see the corresponding points on the graph highlighted. How would the effects of this technology compare to those of MBL, where the motion and the graph happen concurrently in real time, and also occur physically in front of the student, as opposed to on a screen?

Outline of proposed work

We propose to conduct a study to begin investigating this area while providing answers to some of these questions. First, a proof of concept must be built and pilot-tested. An experimental setup must be designed that is appropriate for the examination of phenomena that illustrate the principles of conservation of momentum and mechanical energy in different collision situations: elastic, inelastic and perfectly inelastic (as in the ballistic pendulum) and also with different mass ratios for the colliding objects. This setup must be suitable for analysis with both MBL and VBL so that the effects of these two technologies can be directly compared. The need for this development is best illustrated by looking at the traditional apparatus for the ballistic pendulum experiment.

In this setup, a small ball is launched by a spring gun into a target that is pivoted on an axis, so that after the perfectly inelastic collision of the ball and target, the ball and target swing up. Measuring the height to which the ball and target rise after the collision and applying conservation of mechanical energy to the swing, and then conservation of momentum to the collision itself, allows the student to find the ball's speed. In order to do this, a student must have a strong theoretical understanding of the ideas of conservation of momentum and conservation of mechanical energy, including a good understanding of where and how those principles apply to a real, in this case rather complicated, physical situation. Many students in introductory physics courses lack such an understanding; thus, the use of the traditional setup may result in a mechanical application of a procedure given by the instructor to find the value of the speed, and not in any furthering of understanding of the concepts involved. Presumably, the instructor's goal is rather to use the experiment as an instantiation that allows the student's understanding of the concepts and principles involved to be probed and improved. In fact, this experiment is often seen as a "capstone" experiment that has the goal of allowing students to integrate several fundamental principles of mechanics. This goal is defeated when, because of the very same lack of understanding that the experiment is intended to remedy, students simply apply a procedure whose purpose and meaning is obscure to them.

In addition, the traditional ballistic pendulum setup is not ideal for analysis using the MBL approach, nor, for that matter, is the VBL approach completely adequate. The traditional apparatus was developed for measuring the rather large speed of a bullet or spring-gun-launched ball. To determine this speed most accurately, the distance of travel of the projectile from the launching point to the target needs to be as short as possible. On the other hand, if the goal is to further students' conceptual and procedural understanding, this feature is a limitation, as the projectile's relatively large speed and short distance traveled makes it difficult for students to follow the collision process in any detail. This is true even with VBL tools, as we have discovered in preliminary work on this problem. If the setup is to be suitable for helping students gain understanding through its manipulation and analysis, then the processes involved must be simpler to follow visually. For example, it must allow for relatively small "bullet" speeds so that students can follow the details of the collision and its aftermath more easily.

We are testing a setup with two colliding carts, either on an air track or a low-friction track, with one of the carts (the target) attached to a spring, whose compression takes the place of the pendulum's rise in the traditional ballistic pendulum apparatus. The data acquisition for such a setup is simple, by using either two motion probes (one tracking each cart) or a video camera. This setup allows the possibility of a wide range of (rather low) speeds of the "bullet" to be used, thus permitting students to develop an intuitive sense of the phenomenon by observing the process. The masses of the carts can also be varied easily, so that students can observe the dependence (lack of dependence, actually) of the general principles on the specific masses involved. A further advantage of such a setup is that motion is one-dimensional, making it easier for students to focus on the general principles involved. In the traditional ballistic pendulum setup, the angular motion of the pendulum must be taken into account in order for the results to be accurate.

On the other hand, we expect that the software and hardware tools already developed for MBL and VBL are entirely adequate for data acquisition and analysis with such a modified experimental apparatus. Such tools are available and in use at Wittenberg in the introductory physics laboratories. We plan to use PASCO or Vernier signal interfaces, motion sensors, and software (such as Science Workshop) for the MBL experiments. The analysis of the data can be carried out in Science Workshop, or data can be exported into an Excel spreadsheet and analyzed (which, however, removes the possible advantage of simultaneity from the MBL approach). For the video analysis, we plan to use Lenox Softwork's Video Point software, or some similar commercially-available software package.

Certainly, the proof of concept should not be limited to the actual apparatus used. As some researchers have noted (Linn *et al.*, 1987), the cognitive effects of MBL, as of any other kind of learning laboratory work, are a product of the learning event of which the technology is a part. Consequently, this proof of concept must consist of a complete instructional intervention calling for student exploration of collisions under a variety of conditions (prescribed as well as student-determined) and using one or the other of the two approaches (MBL or VBL). This will require the development of a lesson plan in the form of a prototype laboratory protocol for use with the setup and the possible approaches for analysis. Such a protocol would be expected to be useful to others in and of itself. Even more benefit, however, would be realized if the process of instructional development were documented and made available for others' use. Thus, we intend to analyze and discuss the design, development, and implementation process, and to disseminate the results of the analysis for those interested in developing similar instructional interventions. In this way, by documenting the instructional development process and examining the changes required for its implementation, this project may also contribute to the area of the effects on pedagogy of introducing MBL and VBL technologies in the teaching of physics laboratories.

A second component of the project is the identification of the learning variables of significance. As mentioned before, graph-related abilities and even conceptual understanding have been considered in MBL- and VBL- related literature. We expect that a major goal of this project will be to assess conceptual change (Dykstra, Boyle & Monarch, 1992) related to the concepts of conservation principles. However, research in the area of science education points to the need to consider other general outcomes. Among these are the ability to explain ideas and procedures, to formulate and test hypotheses, to work with colleagues in a productive manner, to ask penetrating questions and make helpful comments when you listen, to choose interesting problems to work on, to design good experiments, and to have a deep understanding of theories and questions in the field (Collins, Hawkins & Frederiksen, 1993). Others are the importance of situating decision making in a social context (such as that of collaborative groups), of promoting student discussion and, thus, of helping students gain a perspective on the nature of scientific inquiry (Kelly & Crawford, 1996). In addition to these general outcomes, other more specific outcomes may be expected, based on research in the area of physics education. Among these are helping students in physics achieve a deep, conceptual understanding of the subject and helping them develop powerful problem-solving skills (advancing from a novice to an expert problem-solver: Mestre, Dufresne, Gerace & Hardiman, 1993), helping students change from an engineering approach (manipulating variables to optimize a process to produce desired outcomes) to a science model (searching to identify causal relations between variables and outcomes: Schauble, Klopfer & Raghavan, 1991), and helping students construct the proper disciplinary declarative, procedural, and strategic knowledge by focusing on conceptual understanding.

With this wealth of information, it is therefore necessary to spend considerable effort in examining the possibility of developing a strong rationale linking some of these desired outcomes to relevant MBL and VBL characteristics. This will be undertaken concurrently with the development of the instructional intervention.

The experimental test of the derived hypotheses will be the third component of the project. For this, the instructional intervention will be implemented in several different courses at

Wittenberg; there also is the possibility of recruiting students at other schools. An appropriate experimental design will be developed to ensure the quality of the data obtained.

Reasons for conducting the study

What are the reasons for undertaking this project at this time? First, from a decision-making point of view, studies have been conducted that are, at best, inconclusive as to the benefits of MBL in many areas other than graph-related skills. But many practitioners tout the potential advantages of the approach over traditional labs. However, if an institution wants to embrace the approach, there should be a more solid indication of what can be gotten for the money, since there is quite a bit of investment needed, in terms of equipment but also in implementation costs such as retraining of instructors, production of instructional materials, and reorganization of class management. Thus, it is a matter of educational policy.

Second, one can take a science education point of view. The previous studies conducted with pre-college students may point to benefits that are of lesser importance with college students, and particularly with students who are majoring in science, applied science, or technological areas. But recent research in science education indicates that better science training requires an emphasis on developing skills related to problem-solving, through collaborative planning, designing, carrying out, and interpreting relevant experiments (Arons, 1993). The potential of MBL and VBL to contribute to these outcomes should be explored. Thus, it is a matter of better training in general science abilities.

Third, from a modern physics education point of view, many authors claim that physics instruction has to change (to the point of the claim having become commonplace). The most important part of the change relates to what that instruction should foster in the student (Redish, 1994). Most MBL research available has dealt with introductory topics in physics, and specifically with kinematics and graphing skills; it is still a question whether the approach would not only be appropriate to other topics and higher levels, but also foster other desired outcomes at those levels. Thus, it is a matter of better training in physics.

Method and Procedure

The project will be carried out over a two-year period and will comprise three main phases, the first two to be undertaken concurrently.

The first phase, as mentioned before, involves the development of the proof of concept. This is an instructional development activity that will largely follow a prototyping methodology, which is considered most appropriate for technology-rich instructional development.
- An apparatus or setup, much along the lines described before, has to be developed. This must be guided by a preliminary content analysis, much of which was done while preparing

this proposal: it has to serve the purposes of suitability for the approaches envisaged, and adequacy for target population comprehension; all the while, obviously, dealing with the primary subject of study.
- A first evaluation of the proof of concept must help with decisions concerning contextual instructional variables (such as the ranges of intervening parameters to suggest to students, the confines for practicable team work, the limits for core and extension activities to fit reasonable class-time constraints, etc.) as well as on the suitability of the activity for the study framework (does it lend itself to the examination of the learning variables chosen for the study).
- The final step is the write up of protocols for student use and manuals for instructor guidance, as well as of a preliminary technical report on the development process. The protocols will be first used in the experimental phase of the present study; but special care will be put into giving them, as well as the instructor manuals, a form suitable for dissemination to all people interested in using the instructional intervention based on this lab activity. The technical report is intended to fill another important role: it should help people interested in developing similar instructional interventions, providing some guidance on development method and design principles in the form of a case study. The instructor manuals and the technical report will be completed in the second year of the project.

The second phase comprises the study of variables of significance. As demonstrated in the first part of this proposal, we have conducted a significant examination of the literature on the area. However, it is felt that further refinement of the rationale will provide a structured framework for the study. For example, we know that we need to go much beyond the skills related to understanding graphs that were examined by the majority of MBL studies. But different avenues are possible, and we believe it is necessary to dedicate a significant effort to analyze them. One that is most interesting is the study of conceptual change, to which much attention is paid in the literature in science education. Without precluding other avenues, we will be giving special consideration to this one when building our own framework. The study, which will largely be a critical review of the literature, will help us identify the variables of significance to include. It will thus also be the basis for the particular method and instruments to use. For example, within conceptual change a theoretical framework may indicate the appropriateness of using or adapting existing instruments (such as the FCI or MBT: Hestenes, Wells & Swackhamer, 1992; Hestenes & Wells, 1992), or applying an existing methodology (such as RepGrid: Winer & Vázquez-Abad, 1997).

This second phase will be undertaken concurrently with the first one, ending in the development by the end of the first year of a plan (research design) for the experimental study with students.

The third phase comprises the experimental study with students and the analysis of results. This study will take place mainly at different times during the second year, with analysis following immediately after data collection. Although the actual research design must wait the end of the first year, we can anticipate some combination of a quasi-experimental study involving groups undergoing different levels of the intervention (e.g., only MBL, only VBL, a combination of both), with or without a control group; and other concurrently run studies (e.g., a descriptive, qualitative, in-depth analysis of conceptual changes in selected samples of subjects).

Collaboration details. On the basis of the proposed method, we can explain the collaboration aspects sought and each of the investigator's team's responsibilities. Phase one: The development of the apparatus for the study will largely be undertaken by the Wittenberg team. The UdeM team will advise on all instructional aspects of protocol and guide development. The technical report will be a shared responsibility. Phase two: The study of variables of significance will largely be undertaken by the UdeM team in close consultation with the Wittenberg team. The production of the research design and/or experimental plan will be a shared responsibility. Phase three: The experimental study will be undertaken mainly at Wittenberg with possible participation of students from other campuses. However, members of the UdeM team may be present at some specific experimental sessions (e.g., when some interviews are deemed required to collect qualitative data). Analysis of results will be distributed among the teams and interpretation and final report writing will be a shared responsibility.

Dissemination of results

Plans for dissemination of the results of this project include the following:

- Presentations at future AAPT, NARST and AERA meetings. Already, a presentation is planned for the April 1998 AAPT/APS meeting on the principles underlying the proof of concept and sample data obtained with certain setups;
- Publications in refereed journals such as Physics Teacher and J. of Res. in Science Teaching;
- Technical reports intended for practitioners (e.g., lab protocols) and researchers (e.g., literature review, report of results, etc.).

Qualifications of the principal investigators

Dr. George is now in her fifth year of teaching at the college level. She has been interested in MBL/VBL approaches for some time, and indeed has used various types of MBL throughout her teaching career. One of her major areas of focus in teaching has been in the laboratory, and in particular, in developing and using computer-based laboratory experiences for students at introductory and intermediate levels. In addition, she has a long-standing interest in educational research; as a graduate student, she took a course (as an auditor) in the chemistry department on current problems and research in chemistry education. Her interest became more focused during her participation in the NSF-sponsored *Seminar on Teaching Introductory Physics Using Interactive Teaching Methods and Computers* held at Dickinson College in June 1997. With more knowledge and discussion of the topic she became aware of the need for conducting research, in the form of structured studies, to better direct her own practice as an instructor of college-level physics, and to contribute to the growing yet incomplete body of knowledge in the area. At Dickinson, she met Dr. Vázquez, with whom this proposal was developed. The proposed project would therefore provide an opportunity for her to develop interdisciplinary connections and expertise in educational development and research. Although this is a new research area for Dr. George, she has had experience in directing and supervising student assistants in research. She has supervised two undergraduate students in research projects in nuclear physics; the results of one of these projects have been incorporated into a paper recently published in *Physical Review C*.

Dr. Vázquez is currently conducting research on science education, mainly on aspects of learning physics with microcomputer-based-laboratories and Web-based applications; on collaborative learning with distributed science laboratories; and on conceptual change in physics learning. He coordinated the Laboratory for computer-based evaluation and teaching in mathematics and science (*LIDÉ*) of the Faculty of Education at the Université de Montréal; established in 1991 with the aim of helping improve the teaching and learning of high-school science and mathematics through the use of information technology, the laboratory was, until its closing in 1996, a partnership project with the Commission scolaire Ste-Croix (a school district in the Montreal region) and IBM Canada, and had the financial participation of Dupont Canada and the Quebec Ministry of Education. Stemming from his work on microcomputer-based laboratories at *LIDÉ*, Dr. Vázquez was invited in 1993, 1994 and 1995 by the Ministry of Education of the Province of New Brunswick to conduct workshops on the use of IBM’s Personal Science Laboratory in grades 7-12 Physics and Chemistry teaching; 70 teachers participated in all.

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