

Spending Time On Design: Does It Hurt Physics Learning?

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Abstract. This paper is the first in a series of three describing a controlled study “Transfer of scientific abilities”. The study was conducted in a large enrollment student introductory physics course taught via Investigative Science Learning Environment. Its goal was to find whether designing their own experiments in labs affects students’ approaches to experimental problem solving in new areas of physics and in biology, and their learning of physics concepts. The theoretical framework for the design of the study was based on transfer theories such as “preparation for future learning”, “actor-oriented transfer”, “transfer of situated learning” and “coordination classes”. In this paper we describe the design of the study and present data concerning the performance of experimental and control groups on multiple-choice and open-ended exam questions and on the lab exams that assess student understanding of the physics and the reasoning processes used in the lab experiments. We found that the experimental group outperformed the control on lab-based and traditional exams and the difference increased as the year progressed. The project was supported by NSF grant DRL 0241078.

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INTRODUCTION

This manuscript is the first of three papers that describe an experimental design study in an introductory course whose goal was to investigate the effects of design labs on student learning of physics and their acquisition and transfer of scientific abilities.

Scientific abilities are approaches and procedures that scientists use when engaging in the construction of knowledge or in solving complex problems [1]. In this study all students enrolled in the course attended the same large room meetings and recitations that followed the *ISLE* curriculum [2]. However, they were randomly split into two groups in the labs. The experimental group designed their own experiments. Their scaffolding included questions concerning the scientific abilities needed for the *ISLE* design labs [3] and on self-assessment rubrics [1]. In the control group students performed the same experiments but with the design provided in the write-up and supported by conceptual questions that helped students work through the physics. Throughout the semester the groups were compared on their physics learning. At the end all students performed two lab transfer tasks: one to design an experiment to investigate a physics problem in new area of physics and the other an

experiment in biology. This paper describes the part of the study related to the comparison of the groups on the paper-and-pencil exam problems and lab-based problems. The research question in this paper is: if students in the labs focus on designing their own experiments without having the “right answer” and on the elements of the scientific investigation instead of on solving physics problems, do they learn less physics than those who have a good experimental design provided for them and more opportunities to engage in physics problem solving? Two other submitted papers describe the aspects of the project related to transfer in the physics and biology content.

MOTIVATION

There are two big motivations for this study: (1) Recent reports concerning science and engineering education encourage student acquisition of conceptual and quantitative understanding of physics principles *and* also the acquisition of abilities to: design their own experiments, reason from the data, construct explanatory models, solve complex problems, work with other people, and communicate [4-7]. Should we spend time on the development of these latter abilities

or this will harm students' acquisition of physics conceptual learning and ability to solve traditional problems? (2) Many experiments indicate that the ability to transfer what is learned in physics to other unstudied physics areas, to other academic disciplines, and to work after academia is lacking. Can students transfer what they learn in our physics design labs to other unstudied areas of physics and to other academic disciplines—the subject of our other two papers?

THEORETICAL FOUNDATION

Transfer As this study is a part of a larger “transfer” study, we briefly describe the theoretical perspectives that informed the design of the whole project. When designing the learning environment for the experimental group, we carefully followed the recommendations of the literature on how to create a learning environment that promotes transfer.

As mentioned above, the purpose of the whole project was to determine if students in design labs are able to transfer the scientific abilities that they learned during one semester into new physics content and into biology. In other words, to find whether they apply the habits of mind learned in the labs when they face a new problem for which they do not have content knowledge or experimental skills.

Transfer refers to the ability to apply knowledge, skills, and representations to new contexts and problems [8-10]. Research shows that achieving transfer is difficult [11]. However, new work of Lobato shows that transfer occurs often and the problem is in its recognition by researchers, not its existence [12]. There are several theoretical models of transfer [13, 14, 12]. The most relevant to this study are direct applications transfer, recognition of affordances, preparation for future learning transfer, and actor-oriented transfer. For any kind of transfer to occur, the learning environment should have such features as: focusing students' attention on pattern recognition among cases and induction of general schemas from a diversity of problems [15]; engaging students in meta-cognitive reflection on implemented strategies [16]; and presenting students with contrasting cases.

DESCRIPTION OF THE STUDY

The study was conducted in the first (fall) semester of an introductory physics course for science majors (the total enrollment was 193; the number of students attending various activities varied through the semester). There were two 55-min lectures, one 80-min recitation, and a 3-hour lab per week. There were

two midterm exams, one final exam and two lab exams. All students learned through the same *ISLE* curriculum [2] in large room meetings and in smaller recitations. The lab sections were split into two groups: design labs (4 sections) and non-design labs (4 sections). Students registered for the sections in March of the previous academic year. In the previous years we found no difference in performance of lab sections on exams, thus we can assume that during the experimental year the student group distribution was random. During the semester, students were not informed about the study. At the end, we disclosed the procedure and students signed a consent form allowing us to use their work for research.

To make sure that the design group and non-design group were equal in learning ability, we administered Lawson's test of hypothetico-deductive reasoning in the first lab session [17]. Coletta and Philips [18] found that student's learning gains are strongly correlated with their scores on this test. Our lab sections were statistically the same. To ensure that the treatment was the same too, we used the same three TAs to teach the labs. Two of the TAs taught one design and one non-design section and the third TA taught two of each. All TAs were members of the PER group, highly skilled in the interactive teaching.

Design labs In these labs students had to design their own experiments. The scaffolding was provided through write-up questions that focused their attention on the elements of the scientific process: representing the situation, deciding on the experiment, analyzing experimental uncertainties, etc. Students used self-assessment rubrics to help them write lab reports [3]. A sample write-up for one lab experiment is provided in the Appendix. The TAs did not help students design experiments and when students had difficulties, they asked questions and provided hints but did not answer their questions directly.

At the end of each experiment students had to reflect on the purpose of the experiment, its relationship to their everyday experience, and its place in an overall scientific process. Lab homework that students did after each lab contained reading passages with reflection questions. Student had to analyze stories about historical developments of several scientific theories and applications such as the nature of AIDS, prophylactics, and pulsars. They had to identify the elements of scientific inquiry that are present when scientists answer new questions or apply knowledge. The purpose of the passages was again to help students reflect on the common elements of a scientific investigation.

Non-design labs In these labs students used the same equipment as in design labs and performed the same number (sometimes even more) experiments. The write-ups guided them through the experimental

procedure but not through the mathematics. Students had to draw free-body diagrams, energy bar charts and other representations to solve experimental problems but they did not need to think about theoretical assumptions – these were provided to them in the text. These labs were not cook-book labs; we call them non-design reformed labs. These labs had homework as well—mostly physics problems that prepared students to do the next lab. The TAs taught the labs differently. They provided an overview of the material at the beginning of the lab and then later if students had questions, they answered these questions.

To ensure that students’ and TAs’ behavior was indeed different in the labs, a trained observer used the method described by Karelina and Etkina [19] to keep track of the time spent by a group of students on different activities. The length of this paper does not allow us to elaborate on the details of the method. The observer “timed” one design group and one non-design group each week, observing 20 3-hour labs.

The part of the study reported in this paper relates to students performance on four exams: the lab practical exam, two midterms, and the final. The practical exam had questions related to the lab experiments and questions that probed student understanding of the physics behind the experiments (see the example in Appendix 2). The regular exams had a multiple choice portion and an open ended portion (3 problems per midterm and 5 on the final). During the comparison, the score on the Lawson’s pre-test was held as a covariate. Thus the results are for the students matched by their pre-test score.

FINDINGS

Observations of student activities in the labs: The observer found that students in design labs on average spend more time making sense of the experiment and writing the results (see Table 1). The total time was larger too, although both groups officially had 3-hour labs. Non-design students chose to leave early.

Table 1: The average time in minutes that students spent on different activities in the labs: SM-sense making; Writ.- writing; Proc.-Procedure; Rd. –reading; TA – TA help; OT – off task.

Design group							
	SM	Writ.	Proc.	Rd.	TA	OT	Tot.
Labs 1-10	37	66	24	5	18	8	159
s.d.	10	12	13	1.7	16.0	9.2	25.9
Non-design group							
Labs 1-10	14	41	20	4	17	2	96
s.d.	8.4	15.1	10.7	3.2	12.8	1.4	30.8

Lab practical: The lab exam was held during the 6th week of classes. All students took the whole 3 hours to

complete the exam. The average score of the design group was of 11.5/15; the average of the non-design group was 8.5/15. The groups were different at the $p < 0.001$ level of significance.

Midterm 1: The scores of the design group were slightly lower than the non-design on both the multiple-choice and the free-response parts of the first exam, but the difference was not statistically significant.

Midterm 2: The design group scored significantly higher than the non-design group on exam 2—multiple choice [$p=0.034$] and overall [$p=0.05$] with the pre-diagnostic test as a covariate.

Final exam: The design group scored significantly higher than the non-design groups in the free response questions [$p=0.043$]. More detailed analysis revealed that students in the design group outperformed non-design students on all problems where they had to identify or analyze assumptions that they used in a solution.

The differences between the groups persisted in the second semester when all students had design labs. On the final exam in the second semester students from the fall semester design group significantly outperformed non-design group (Free Response $p = 0.008$, Overall $p = 0.014$). The average on the exam for the design group was 167, for the non-design was 156 (out of 240).

DISCUSSION

As we discussed earlier, one purpose of the project was to find whether students who design their own experiments could transfer learned abilities to new content. Although we do not describe the transfer experiment in this paper, we note that there were significant differences between the two groups on the transfer tasks (see other papers in this volume). This paper concerns physics learning – do the design students who struggle designing their own experiments, write long and detailed lab reports, analyze historic passages about scientific discoveries, and perform the labs in a totally constructivist environment miss on learning physics concepts and applying them to problem solving? We found that design students mastered the physics content of the labs better than their counterparts in non-design labs and more importantly learned physics content at least as well as the control group. Furthermore, the difference between the groups became even larger at the end of the second semester. The students possibly had developed a more independent way of thinking that helped them in future learning. One counter argument might be that design students spent more

time in the labs and thus learned more. However, non-design students had the same time allocated for the labs in the curriculum, they just did not use this time due to the structure of the labs.

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Appendix: Design lab: The energy stored in the Hot Wheels launcher

The Hot Wheels car launcher has a plastic block that can be pulled back to latch at four different positions. Your need to determine the elastic potential energy stored in the launcher in each position.

Available equipment: Hot Wheels car, track, launcher, meter sticks, ruler, tape, timer, scale, spring scale, motion detector. Write the following in your lab report:

- a) Make a rough plan for how you will solve the problem. Make sure that you use two methods to determine the energy. Include a sketch in a procedure brief outline.
- b) In the outline, identify the quantities you will measure and describe how you will measure each quantity.
- c) Construct free body diagrams, and energy and/or momentum bar charts wherever appropriate.
- d) Devise the mathematical procedure to solve the problem. Decide what your assumptions are and how they might affect the outcome.
- e) Perform the experiment and record the data in an appropriate manner. Determine the energies.
- f) Use your knowledge of experimental uncertainties to estimate the range within which you know the value of each energy.

Non-Design lab: Energy stored in the Hot Wheels launcher:

The Hot Wheels car launcher has a plastic block that can be pulled back to latch at four different positions. Your first task is to determine the elastic potential energy stored in the launcher in each of these launching positions. *Procedure:* Launch the car vertically starting at one of the launching positions. By measuring the maximum height the car reaches, you should be able to decide the original elastic energy stored in the Hot Wheels launcher.

- a) Measure the mass of the Hot Wheels car.
- b) Hold the Hot Wheels car launcher so that it is oriented almost vertical—so the car does not fall out when placed in the launcher. Experiment a little with shooting the car almost vertically up into the air.
- c) Place a meter stick beside the launcher and note the position on the meter stick of the front of the car when the car is ready for launch. Hold the launcher firmly and release. Find the vertical distance the car traveled.
- d) Repeat this measurement four times. Take the average of the four vertical distance measurements and calculate the standard deviation of the measurements. Calculate the fractional uncertainty in the vertical distance measurement ($\Delta h/h$).
- e) Repeat the measurements for the other three positions.

- f) *Analysis:* Construct a work-energy bar chart for the process starting with the car resting on the stretched launcher and ending when the car is at its maximum elevation. Apply the generalized work-energy equation
- g) Insert your measurement numbers and determine the initial elastic energy of the launcher. Calculate the fractional uncertainty of the elastic potential energy for each launching position—equal to the fractional uncertainty of the vertical distance traveled times the elastic energy for that launching position.

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