Studying Transfer Of Scientific Reasoning Abilities

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Abstract. Students taking introductory physics courses not only need to learn the fundamental concepts and to solve simple problems but also need to learn to approach more complex problems and to reason like scientists. Hypothetico-deductive reasoning is considered one of the most important types of reasoning employed by scientists. *If-then* logic allows students to test hypotheses and reject those that are not supported by testing experiments. Can we teach students to reason hypothetico-deductively and to apply this reasoning to problems outside of physics? This study investigates the development and transfer from physics to real life of hypothetico-deductive reasoning abilities by students enrolled in an introductory physics course at a large state university The abilities include formulating hypotheses and making predictions concerning the outcomes of testing experiments. (The work was supported by NSF grant REC 0529065.)

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INTRODUCTION

Introductory physics courses are expected to promote scientific literacy, critical thinking skills and help students develop abilities necessary for the 21st century workplace. In their future work our students will need to be able to pose their own questions, to design experiments to test hypotheses or to solve a problem, to collect and analyze real data, and to communicate the details of the experimental procedure [1, 2]. The goal of the study described in this paper is to investigate whether students who learn physics in a specially designed environment [3] that has one of its primary goals the development of scientific abilities [4] can transfer these abilities to other content areas besides physics. In this study we focus on the ability to engage in hypothetico-deductive reasoning, and in particular, on the abilities to formulate a testable hypothesis and to make a prediction of the outcome of the experiment based on the hypothesis.

THEORETICAL BACKGROUND

Hypothetico-deductive reasoning Hypothetico-deductive reasoning has been recognized as one of the reasoning approaches widely used in the practice of science [5]. This reasoning involves devising a hypothesis to explain some observational facts, designing an experiment whose outcome can be predicted using the hypothesis, using *if, then* logic to predict the outcome of the testing experiment based on the hypothesis, carrying out the experiment, comparing the outcome with the prediction, and rejecting the hypothesis if there is a mismatch of the outcome and the prediction.

Examples of hypothetico-deductive reasoning can be found in abundance in the history of physics. One of them is by Rutherford: "On consideration, I realized that this scattering backwards (*observational fact*) must be the result of a single collision… It was then that I had an idea of an atom with a minute massive center carrying charge (*hypothesis*). I worked mathematically what laws the scattering should obey, and I found that the number of particles should be proportional to the thickness of scattering foil, the square of the nuclear charge, and inversely proportional to the fourth power of velocity (*prediction*) These deductions were later verified by Geiger and Marsden in a series of beautiful experiments (*testing*) ("Development of theory of atomic structure", cited in Holton and Brush [6]).

One of the important aspects of hypothetico-deductive reasoning is the understanding of the difference between a hypothesis and a prediction. A hypothesis is some general explanatory statement and a prediction is a description of an outcome of a particular experiment that should occur if the hypothesis is true.

It turns out that the development of hypothetico-deductive reasoning is not only important for students' future work but for their present learning. Results reported by Coletta and Philips [7] suggest that

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students who have a higher level of this reasoning have higher learning gains.

Transfer: Physics as an experimental science yields itself to the development of hypothetico-deductive reasoning naturally. However, as most of our students in the future are going to reason outside of content of physics, it is useful to know whether they can transfer this reasoning ability to a different content area. Transfer refers to the ability to apply knowledge, skills and representations to new contexts and problems [2, 8, 9 10]. Research shows that achieving transfer is difficult [11]. There are several theoretical models of transfer, and in the proposed study we will address the Direct Application model which considers "the ability to directly apply one's previous learning to a new setting or problem" [8]. Transfer can be near or far. When a situation in which a person needs to apply knowledge or skills is close to the situation in which she learned the knowledge or skills, the transfer is near. If the content or context is different, or the new task is given much later than the training task(s), the transfer is far [9].

To facilitate transfer, instructors may focus students' attention on pattern recognition among cases and induction of general schemas from a diversity of problems [12]. Another strategy is to engage students in meta-cognitive reflection on implemented strategies [13, 14].

ISLE LEARNING SYSTEM

The Investigative Science Learning Environment [3] models some of the processes that scientists use to construct knowledge. Students start each conceptual unit by analyzing patterns in experimental data and construct possible explanations or mathematical relationships. Then students test their constructed ideas by using them to predict the outcomes of new experiments, and possibly revising their ideas if the outcomes do not match the predictions. Hypothetico-deductive reasoning plays a central role in this process. In addition to practicing it in large room meetings (our word for lectures) where the instructor leads them through the steps of the reasoning, students engage in it in laboratories, where they often need to test hypotheses constructed in large room meetings or test hypotheses that are based on students' alternative ideas. Students work in groups to design their own experiments. Write-ups for *ISLE* labs do not contain instructions on how to perform the experiments but instead guide students through various aspects of a typical experimental process and reasoning and after the experiments is done ask students to reflect on the steps they took. Students' use self-assessment rubrics that scaffold their work on experiments and help them write lab reports [15]. There are several specific rubrics related to the ability to design experiments to test hypotheses and to make testable predictions. Two of them relevant to the study are shown in Table 1. The rubrics can also be used to score student work to find whether they acquire the desired abilities. Rubrics have been validated and trained raters achieve a high degree of consistency using them [4].

The *ISLE* approach combined with open-ended tasks supplemented with reflection and rubrics has many elements that have shown to promote transfer. Thus we hypothesize that students, who learn physics through *ISLE* and use scientific ability rubrics to self-assess their work, should not only acquire scientific abilities but also be able to transfer them. This hypothesis is based on the assumptions that students acquire the understanding of the abilities, can recognize patterns in laboratory tasks with the help of rubrics, abstract the abilities from the tasks, and map these patterns into new situations. To test whether students transfer the abilities described above we conducted the following study.

DESCRIPTION OF THE STUDY

The study was conducted in a large enrollment (190 students) introductory physics course for science majors. There were two 55-min lectures, one 80-min recitation and a 3-hour lab each week. Prior to the experiment, students conducted four labs and had a practical exam. In two of the labs and in the practical exam they had to test hypotheses using hypothetico-deductive reasoning. In large room meetings the instructor emphasized the importance of this reasoning and reflected on every instance when this reasoning was used.

For example, in week 2 of the first semester, students had to design an experiment to test a proposed hypothesis [in this case the hypothesis was incorrect]. The write-up for the experiment is shown below.

Design an experiment to test the following hypothesis: An object **always** moves in the direction of the unbalanced force exerted on it by other objects.

a) State what hypothesis you will test in your experiment.
b) Brainstorm the task. Make a list of possible experiments. Decide what experiments are best.
c) Draw a labeled sketch of your chosen experiment.
d) Write a brief description of your procedure.
e) Construct a free body diagram of the object.
f) List assumptions you make. How could they affect the outcome?
g) Make a *prediction* about the outcome of the experiment *based on the hypothesis you are testing*.

h) Perform the experiment. Record the outcome.
i) Make a judgment about the hypothesis based on and the experimental outcome.
j) Discuss in your group the difference between a hypothesis and a prediction.

During the first 55-min exam of the semester (week 5), one of the 12 questions that students had to answer was as follows: Write a paragraph describing when in your future work you might need to test an idea by using it to predict an outcome of a new experiment. First choose an idea; then use it to make a prediction of an outcome of a possible experiment, and then describe a possible outcome that will rule it out.

According to the classification of transfer by Barnet and Ceci [9], the transfer we were examining was far in terms of knowledge domain, physical context (exam hall instead of a physics lab), functional context (writing an answer to a question versus designing and performing an experiment), social context (individual versus group) and modality (exam versus a lab). To have some control groups we later posed the same questions for the beginning students in a PhD program (n=9) and advance graduate students in the Graduate School of Education (n=12) and undergraduate students in a third year biology course (n=8) (who had a physics course prior to this). None of these subjects were taking physics at that time. We had a group of 12 physics students but had to discount this sample because we were not sure whether the data were reliable.

Three graders scored student responses using the rubrics for two abilities: an ability to identify the idea to be tested and an ability to make a reasonable prediction based on the idea (see Table 1). The discrepancies in the scores were discussed and the scoring continued until we agreed on all of the scores.

A representative example of students' responses from the experimental group is shown below. We also provide annotations in Italics to help the reader see how we scored the responses.

Student A

When studying the populations of the Chesapeake Bay Blue Crab, I've noticed the total population over a span of 5 years has decreased (*observed fact*). I formulate an idea that the population is decreasing due to overcrabbing by local fishermen (*idea, or hypothesis*). I predict that by placing regulations on the fishermen to reduce the crab catch, the population of the Blue Crab will increase dramatically over next 3 years (*prediction*). Once the regulations have been in place, we've noticed that the population of the Blue Crab has drastically decreased even further (*outcome of testing experiment*). Due to this outcome, we've concluded that the decrease in Blue Crab populations is NOT due to overcrabbing by local fishermen (*judgment).*

FINDINGS

Students' responses in the experimental group showed that many of them could describe an idea to be tested but fewer could make a prediction of an outcome of the experiment based on the idea. The most common difficulty we found was that students used the word "testing" as a substitute for "trying". Responses in control groups varied a great deal. Graduate students in both subgroups could formulate an idea to test but had a difficulty coming up with predictions of the outcomes of testing experiments. Most of the undergraduate students could not identify an idea and could not make predictions. Results of the scoring are shown in Figure 1.

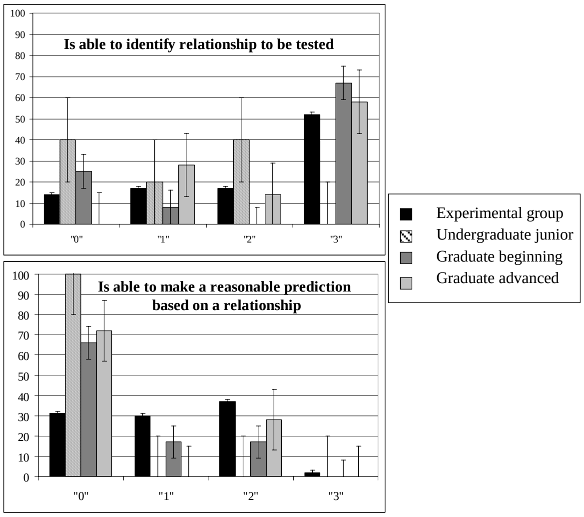

FIGURE 1. Percentage of students in a group who received rubrics scores of 0, 1, 2, and 3. The scores were based on two rubrics: an ability to identify an idea to be tested and an ability to make a prediction based on the idea under test.

DISCUSSION

We found that students in the experimental group could successfully identify an idea to be tested and a relatively high percentage of them could make a prediction based on the idea under test. The latter turned out to be much more difficult for traditionally taught undergraduate students and for traditionally taught graduate students. Could this result be due to an unfamiliar vernacular or due to the nature of the question itself? One of the subjects in a group of physics students at the end of his physics course (we did not include this group in the study due to a low reliability of data collection) wrote: "Why are you asking me this question? I have never seen a question like this before". Another said: "Did we discuss questions like this in class? I do not remember anything like this". These responses are quite alarming. If we agree that hypothetico-deductive reasoning is important for the practice of science and that most of our students in introductory courses will be related to some aspect of science in the future (even only as consumers and citizens), then we should place more emphasis on helping students develop this reasoning and transfer it to areas out of physics. Examples of tasks that develop this reasoning in an introductory physics courses can be found in [16]. We speculate that the reasons for the success were repetitive attention to these aspects of learning in large room meetings and labs, meta-cognitive processes encouraged by the use of self-assessment rubrics and followed up in lectures, and the fact that students had to struggle in labs to design experiments. We plan to have a control study to find if these results are due to the maturation of the subjects or if we observed some real transfer.

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15. Rubrics can be found at http://paer.rutgers.edu/scientificabilities

TABLE 1. Rubric descriptors for two scientific abilities.

Scientific Ability	0 - Missing	1 - Inadequate	2 - Needs some improvement	3 - Adequate
Is able to identify the idea (or the hypothesis) to be tested.	No mention is made of an idea.	An attempt is made to identify the idea but is described in a confusing manner.	The idea to be tested is described but there are minor omissions or vague details.	The idea is clearly stated.
Is able to make a prediction based on the idea (or the hypothesis).	No attempt to make a prediction is made.	A prediction is made but it doesn't follow from idea being tested.	A prediction follows from the idea but does not contain assumptions.	A prediction is made that follows from the idea and incorporates the assumptions.