Dynamic Visualizations of Multi-Body Physics Problems and Scientific Reasoning Ability: A Threshold to Understanding

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Abstract

Visualization is a common and important step in expert-like problem solving across multiple disciplines. Within the context of physics education, significant intervention is often required to develop visualization skills with novice problem solvers. In particular, dynamic multi-body problems require mental models that incorporate multiple objects time-varying in space, which may require significant development of spatial and/or other cognitive abilities. We have investigated student abilities in applying a dynamic visualization to solve a simple multi-body problem and that ability's correlation with scientific reasoning (SR) cognitive ability as measured by Lawson's Classroom Test of Scientific Reasoning (LCTSR). A broad population of students (N=212) attending a regional comprehensive university in the USA were classified into four SR categories based on Piaget's theory of cognitive development: (1) concrete operational, (2) early transitional, (3) late transitional, and (4) formal operational. A short problem was also administered that required students to construct a dynamic visualization to correctly answer. Specifically, the problem involved a situation where two trains leave opposite stations once per hour. The stations are three hours apart. The task was to determine how many trains an observer on one of the trains would see during the three-hour trip between stations. Through analysis of expressed student reasoning, we have found that students answering with 3-4 trains typically have built a visualization based on at least one set of trains remaining stationary. Students answering 6-7 trains typically recognize the evolving nature of the problem and construct an appropriate dynamic visualization with both sets of trains in motion. Students fail almost universally to deploy a successful dynamic visualization when classified below formal operational level. Formal operational reasoners within the population succeed almost universally in applying a successful dynamic visualization. This suggests an epistemological threshold exists, whereby students struggle with constructing dynamic visualizations before reaching a high-formal level of reasoning ability. This has implications for instruction and textbook/classroom problem construction, especially considering that a significant majority of students enrolled in introductory physics courses within our population demonstrate late transitional and below SR levels.

Keywords

Visualizations, physics problems, scientific reasoning, expert-like, multi-body, epistemological, threshold, cognitive ability, dynamic, textbook problems, spatial reasoning.

Introduction

A review of popular introductory physics textbooks in the United States of America reveal that although visualization is often included as an important component of the problem solving process, little discussion is devoted to how students can learn to develop good visualization skills. Furthermore, very few textbook problems in motion incorporate multi-body dynamics, which can arguably be considered more authentic across contexts (Ramirez, Rebollar & Slisko, 2014). Visualization is a common and important step in expert-like problem solving across multiple disciplines. Within the context of physics education, significant intervention is often required to develop visualization skills with novice problem solvers. In particular, dynamic multi-body problems require mental models that incorporate multiple objects time-varying in space, which may require significant development of spatial and/or other cognitive abilities.

Content knowledge gains and process skill development have been linked to several cognitive variables (Moore & Rubbo, 2012; Carmel & Yezierski, 2013; Stamovlasis, Tsitsipis & Papagerogiou, 2012). In particular, scientific reasoning (SR) cognitive ability has been shown to have an effect on content knowledge gains in physics, and has been linked to the development of process skills in experimental methods courses (Coletta & Phillips, 2005; Moore & Rubbo, 2012; Larkins, et al. 2013). Ates & Cataloglu (2007) correlate formal reasoning level to conceptual understanding and problem-solving skills in introductory mechanics. As a process skill, problem visualization may be similarly associated with SR cognitive ability, which should be considered during the development of instructional materials designed for student growth in problem solving.

In the study described in this paper, we have investigated student abilities in applying a dynamic visualization to solve a simple multi-body problem and that ability's correlation with SR cognitive ability as measured by Lawson's Classroom Test of Scientific Reasoning (LCTSR). We present an observation experiment with the purpose of determining if such a link exists between cognitive ability and visualization.

Background

What exactly constitutes SR is both complex and debatable. Lawson suggests that scientific reasoning has a structure that is chiefly hypothetico-deductive in nature and consisting of interrelated aspects, such as proportional reasoning, control of variables, probability reasoning and correlation reasoning (Lawson, 1982 & 2005). Inductive and deductive process are involved, with some researchers intimately linking reasoning with the process of drawing inferences from initial premises (Holyoak & Morrison, 2005).

Piaget's theory of cognitive development includes classification into two formal reasoning levels (concrete operational and formal operational) with a transitional stage between the two (Ginsburg & Opper, 1979). Students classified as mostly concrete operational reasoners are characterized by their appropriate use of logic; however, they struggle with solving problems outside of a concrete context, demonstrating significant difficulty with abstract concepts and hypothetical tasks. Formal operational reasoners begin to think abstractly, reason logically, and draw conclusions from available information. Furthermore, unlike the concrete operational reasoner, they are able to apply appropriate logic to hypothetical situations in most contexts. In this way, formal operational reasoners can begin to think like a scientist, and specifically develop strong hypothetico-deductive reasoning. Transitional reasoners fall between the other two classifications where they find success with hypothetical tasks in some contexts. Lawson describes these levels as Level 0, Low Level 1, and High Level 1, respectively (Lawson, et al., 2000). Lawson further describes a post-formal level of reasoning, which is beyond the scope of this study. In this paper, we will use a similar Piagetian classification scheme. Students are classified into four categories: (1) concrete operational, (2) early transitional, (3) late transitional, and (4) formal operational.

It has been shown that the LCTSR can be used as an assessment of formal reasoning level, and its validity has been established (Lawson, 1978). We have used the 2000 revised, multiple-choice edition of the LCTSR, which assesses reasoning patterns such as proportional reasoning, control of variables, probability reasoning, correlation reasoning and hypothetico-deductive reasoning (Lawson et al., 2000). The LCTSR consists of 12 scenarios followed by two questions each assessing 6 different scientific reasoning patterns. Questions on the LCTSR are pairs with the exception of the last two questions, with scores out of a possible 13. To get a question marked correct, a student must correctly answer both within the pair correctly. One question in a pair elicits a response requiring effective use of the pattern, while the second question has the student describe the reasoning behind the response.

The Two-Train Problem

Figure 1 shows an illustration for the two-trains problem used in this study. This short problem was administered to the student population at the same time as the LCTSR. It requires students to construct a dynamic visualization to arrive at a correct answer. Specifically, the problem involved a situation where two trains leave opposite stations named Beauty and Hope once per hour. The stations are three hours apart. The task was to determine how many trains an observer on one of the trains would see during the three-hour trip between stations.

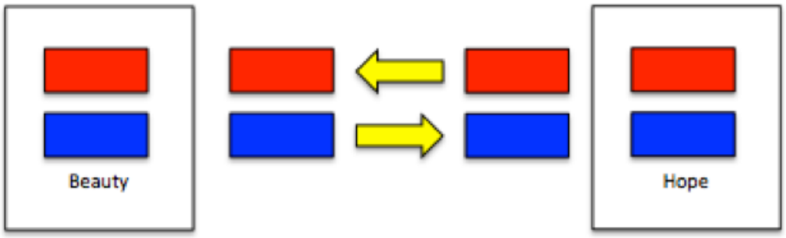


Figure 1. Illustration of the train problem.

The text of the two-train problem as administered to students was as follows:

> *Between two imaginary futuristic cities, named Beauty and Hope, a perfect non-stop train system operates. Every hour a train leaves Beauty for Hope and a train leaves Hope for Beauty. The travel between the two cities takes precisely 3 hours. The question is: how many trains, coming from Hope, will a person count that is travelling from Beauty? The train seen in Beauty, when the travel begins, and the train seen in Hope, when the travel ends, are also counted.*

Students were not provided with an illustration for this problem. Initially, student responses were collected as free response. After free-response data was collected from 75 students, the problem was assigned as a multiple-choice response at the end of the LCTSR for the remaining students in the population.

Student Population

The data set used in this study consists of students enrolled in one of four different courses: (1) a calculus-based physics course for science majors (PHYS 212, N = 57); (2) a first-year science process course for physics majors (PHYS 137, N = 36); (3) a physical science course for non-science majors (PHYS 103, N = 52); and (4) a conceptual astronomy course for non-science majors (ASTR 101, N = 67). These courses were taught at Coastal Carolina University (CCU) in Conway, SC USA. CCU is a comprehensive, regional institution with few graduate programs and a significantly larger undergraduate population. The courses used in this study were chosen in an effort to accumulate data from students demonstrating a wide range of SR abilities. Data were collected over two years (2013-2014).

Scientific Reasoning in the Population

Students in the physical science and conceptual astronomy courses scored significantly lower on the LCTSR compared to students enrolled in PHYS 137 and PHYS 212. Table I shows the average score on the LCTSR for students in the four courses. Students majoring in a Science, Technology, Engineering, or Mathematics (STEM) fields are heavily represented in the latter two courses, whereas the former two courses are populated with students from outside these areas (non-STEM). Table II shows the average score on the LCTSR for non-STEM and STEM students. STEM students score significantly higher than non-STEM students ($p < 0.001$). That students in STEM majors demonstrate stronger scientific reasoning ability is not surprising, since most students typically choose their major based on their strengths.

Figure 2 shows a histogram for the percentage of the population achieving specific scores on the LCTSR. A broad distribution of scores was achieved across all of the courses.

Table I: Average score on the LCTSR ($\bar{S}$) for students in the population.

	$\bar{S}$	N	**std. dev.**
ASTR 101	4.9	67	2.3
PHYS 103	5.0	52	1.9
PHYS 137	6.7	36	2.1
PHYS 212	6.9	57	2.3

Table II: Average score on the LCTSR ($\bar{S}$) for non-STEM and STEM students.

	$\bar{S}$	N	**std. dev.**	p
Non-STEM	4.9	119	2.1	<0.001
STEM	6.8	93	2.2	

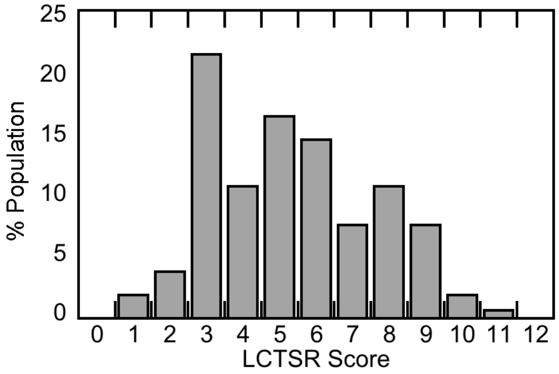


Figure 2. Histograms showing percentages of the population achieving specific scores on the LCTSR.

Using individual student scores on the LCTSR, we classified students into four formal reasoning categories: (1) concrete operational, (2) early transitional, (3) late transitional, and (4) formal operational. Students scoring below a 4 were classified as concrete operational (CO). Students scoring between 5 and 7 were classified as early transitional (ET). Students scoring between 8 and 10 were classified as late transitional (LT). A score above 10 resulted in a classification of formal operational (FO) (Moore, 2012).

Figure 3 shows the distribution of non-STEM and STEM students in the population within Piagetian formal reasoning levels. All levels are represented approximately equally across the entire population, with the exception of formal operational reasoners. This is consistent with a previous study published by the authors of this paper, and previous studies of the general education population in biology courses (Moore & Rubbo, 2012; Johnson & Lawson, 1998).

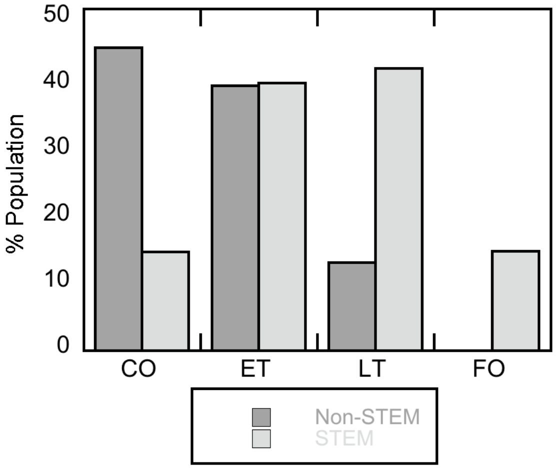


Figure 3. Distribution of formal reasoning level for non-STEM (dark gray) and STEM (light gray) students participating in this study. Concrete Operational (CO), Early Transitional (ET), Late Transitional (LT), and Formal Operational (FO) reasoning levels are shown

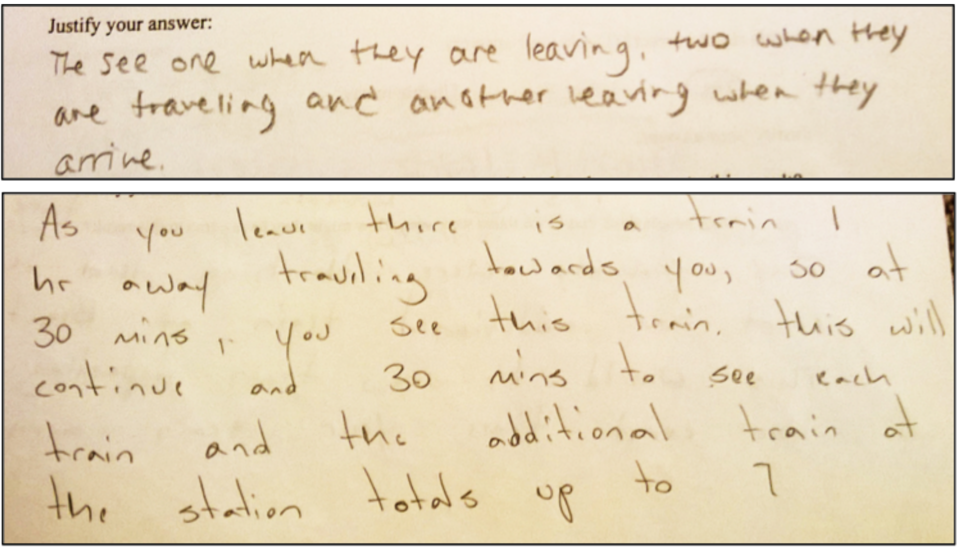
Scientific Reasoning and Dynamic Visualizations

Figure 4(a) shows a student's response to the two-trains problem with reasoning based on a mental visualization that maintains the Beauty to Hope trains as static objects. Evaluation of the free response data shows that students concluding that between 3 and 4 trains will be seen during the trip almost universally demonstrate similar static-based reasoning.

Figure 4(b) shows a student's response to the two-trains problem with correct reasoning that recognizes the motion of both sets of trains. Evaluation of the free response data shows that students correctly answering the question (7 trains) universally demonstrate such a dynamic visualization of the problem. Some students (8% of the free-response population) answered either 6 or 8, but did correctly demonstrate a dynamic visualization of the problem. These students made other errors in reasoning or calculation.

Based on the results from analysing the free-response data, we began administering the two-trains problem as a multiple-choice question added to the end of the LCTSR. Students answering 6, 7 or 8 trains on the multiple-choice version were counted as dynamic visualizers, whereas students answering below 6 were counted as static visualizers.

Table III shows the percentage of non-STEM and STEM students within the population demonstrating a dynamic mental model in answering the two-trains problem. STEM students were significantly more likely to deploy a dynamic visualization than non-STEM students ($p < 0.05$).



(a)

Justify your answer:

The see one when they are leaving, two when they are traveling and another leaving when they arrive.

(b)

As you leave there is a train 1 hr away travilling towards you, so at 30 mins, you see this train, this will continue and 30 mins to see each train and the additional train at the station totals up to 7

Figure 4. Sample of student response to the two-train problem showing (a) a static visualization, and (b) a dynamic visualization.

Table III: Percent of the non-STEM and STEM populations demonstrating a dynamic mental model in answering the two-train problem. STEM students are slightly more likely to utilize a dynamic mental model than non-STEM students (p=0.02).

	Dynamic (%)	**N**	**std. error (%)**	***p***
Non-STEM	24	119	4	0.02
STEM	39	93	5	

Table IV: Percent of students in various formal reasoning level classifications demonstrating a dynamic mental model in answering the two-train problem.

	Dynamic (%)	**N**	**std. error (%)**
Concrete Operational	15	66	4
Early Transitional	35	107	5
Late Transitional	35	69	6
Formal Operational	86	14	10

Table IV shows the percentage of students in various formal reasoning classifications demonstrating a dynamic visualization in answering the two-trains problem. Students classified at the formal operational level are significantly more likely to demonstrate a dynamic mental model in the solution to the train problem than students in lower levels ($p<0.001$). In particular, students fail almost universally to deploy a successful dynamic visualization when classified below the early transitional level, with very little increase with increasing level until the attainment of formal operational. Formal operational reasoners within the population succeed almost universally in applying a successful dynamic visualization, whereas students below this level do not.

This suggests an epistemological threshold may exist, whereby students struggle with constructing dynamic visualizations before reaching a high-formal level of reasoning ability. This thresholding has significant implications for instruction and textbook/classroom problem construction, especially considering that a significant majority of students enrolled in introductory physics courses within our population demonstrate late transitional and below SR levels.

Summary

In summary, we investigated student abilities in applying a dynamic visualization to solve a simple multi-body problem and that ability's correlation with SR cognitive ability. A broad population of student attending a regional comprehensive university in the USA were classified into four SR categories based on Piaget's theory of cognitive development. A short problem was administered that required students to construct a dynamic visualization to correctly answer. Students fail almost universally to deploy a successful dynamic visualization when classified below formal operational level. Formal operational reasoners within the population succeed almost universally in applying a successful dynamic visualization. This suggests an epistemological threshold exists, whereby students struggle with constructing dynamic visualizations before reaching a high-formal level of reasoning ability.

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