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Spatial ability and achievement in high school physics

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SPATIAL ABILITY AND ACHIEVEMENT IN HIGH SCHOOL PHYSICS

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First I must thank my parents, James and Violet Liner, my uncle Dale Liner, and my grandparents, Roylea and Mamie Liner for raising me in an environment where curiosity and knowledge were valued. The patience and love you've shown me throughout my life have led me to become a teacher of patience and dedication. Thank you for the amazing examples you have set.

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ABSTRACT

This study investigates the relationship between a student's spatial abilities and their success in high school physics. First, I investigate whether the success of students in high school physics class correlates with their spatial abilities before taking the class. Second, I investigate whether taking high school physics has an effect on student's spatial abilities. No direct intervention was given to any of the students.

Three instruments were administered to determine the student's spatial abilities, The Perspective Taking/Spatial Orientation Test (Hegarty & Waller, 2004), The Mental Rotation Test (Peters & Laeng, A Redrawn Vandenberg and Kuse Mental Rotations Test:, 1995), and The Paper Folding Test (Ekstrom, French, Harmon, & Derman, 1976). Students were also evaluated on their pre-conceived notions of force and motion using the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992). These four instruments as well as the student's course test averages were evaluated to determine correlation.

Results suggest that there may have been an improvement in spatial abilities as measured by the Mental Rotation Test in the AP course ($n=17, p<0.05$). However, I did not find any correlation to pre-existing spatial abilities and performance in the course.

1. INTRODUCTION AND BACKGROUND

As a high school science teacher, I am always curious as to why certain students outperformed other students in my courses. Some students seem to come into the class already having the ability to “see” physics better than others. While some students struggle to draw an arrow showing the force on an object, other students are able to draw the force vector with ease. Obvious student advantages are work ethic, and math abilities. However, there seems to be something else.

While investigating the concept that there was some other factor affecting student performance, I came across the concept of “spatial abilities” and how they were related to dental education (Hegarty M. , 2008). Essentially, spatial ability is the ability to visualize objects in three dimensions and manipulate them in your mind. Because there are quite a few instances in physics where we are required to visualize objects in three dimensions and because of some of the literature available, I believe there may be some connection between the course and spatial ability.

Piaget states that the first stage of spatial skills, topological skills, is expected to start developing in children as early as three to five years old. (Sorby, 2009). This is observable as children start to put puzzles together. However, the second stage, which involves 3D objects and the ability to image scenes from different viewpoints, doesn’t develop until adolescence. (Sorby, 2009) This means that the students are developing the very skills they need for geometry and physics while we teach them.

The spatial concepts in physics and the timing of spatial development brought two questions to my mind. First, “Are there some activities or classes that increase spatial ability?” Secondly, “Are there courses where students are benefited by pre-course spatial ability?" In relation to the first question, it has been found that college level physics classes have been shown to increase a student's spatial abilities (Pallrand & Seeber, 1984). An article that addresses the second question showed that success in dental school does relate to spatial abilities. (Hegarty M. , 2008). This article concluded that spatial abilities enhanced performance in dental school. In fact spatial ability tests are used to select students for medical education. This study found that grades in restorative dentistry were significantly correlated with perceptual spatial ability. So at least at the college level there appears to be a link between spatial abilities and science courses.

On a high school level, engineering classes have been found to be related to spatial ability in students. (Brudigam, 2011). This study showed that students taking a high school engineering class, in which 3D drafting was involved, had greater posttest scores in spatial abilities than their classmates who had only taken Geometry. A major limitation of their study was the lack of pretest. So there is a chance that students, who later took the engineering class, started out with higher spatial abilities. However, it seems to indicate that the course itself was related to the spatial ability. Surely, the possibility exists that high school physics may have an effect on spatial abilities. Or, that spatial ability enhances a student's achievement in high school physics.

In high school physics we introduce students to vectors, torque, relative motion and free-body-diagrams. The hypotheses of this paper are that not only do these topics require certain amounts of spatial ability, but that learning the subject will increase a student's spatial ability. In calculus based AP Physics we calculate 3D components of vectors and work three dimensional statics problems. Also, the classic demo in which a gyro precesses about its axis involves three dimensional torque calculations which lead me to believe that students need and will learn spatial skills. Even in non-calculus courses we often deal with two dimensional vectors and perceptual abilities. I've experienced students who had an easier time dealing with the three dimensions than others. I've also seen students who struggled to understand the difference between “up” and “North”. These factors combined lead me to investigate the connection between high school physics and spatial abilities.

2. MATERIALS AND METHODS

2.1 Participants

The participants were 93 physics students at Parkview Baptist School in Baton Rouge, LA. Parkview Baptist School is a K-12, non-parochial, private school with a population of 1399 students enrolled from Pre-K to 12th grade. The population is 91% Caucasian, 5% African American, and roughly 1% each Asian, Hispanic, and other.

73 of the students were enrolled in an on-track course, referred to as “College Prep”. This course covers all topics associated with a normal high school physics class including Kinematics, Forces and Motion, Waves, Light, Sound, and Electricity.

The other 20 students completed an advanced placement, AP®, course which is in line with the college boards recommended syllabus for AP Physics C, Mechanics. This first-year physics course covers Kinematics, Force and Motion, Rotational Motion, Torque, and Waves. There were two students that started in the AP course, but transferred to the CP course mid-year. These two students were not included in analysis since they spent roughly half of the year in each course.

Most students at the school (roughly 90%) take physics their senior year. As a result the sample was representative of the population of the school.

2.2 Materials

2.2.1 Force, Motion and Knowledge of Physics

2.2.1.1 Force Concept Inventory

The Force Concept Inventory was used to evaluate the student’s conceptual understanding and growth in Newtonian Physics. The Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992) evaluates a student’s Newtonian understanding of physics. Most students come into physics class with a combination of Aristotelian and Medieval Impetus Theories (Halloun & Hestenes, Common Sense Concepts About Motion, 1985). Thus, most students believe that a force is necessary to maintain motion and that heavy objects fall faster than slow. The Force Concept Inventory is a series of 30 multiple choice questions designed to test a student's Newtonian understanding of forces and motion.

2.2.1.2 Student's Test Scores in the Course

Student's test scores in their respective classes were used to measure their "success" in the physics course. This score was calculated as the total number of points earned on all tests divided by the total number of points available on all tests in the course. This was used as a measure of the students' success in the course as it showed the student's performance on tests without being inflated (or deflated) with homework, projects and possible bonus opportunities. Tests in both courses consist of approximately 20% (by point value) multiple choice and 80% free response. Most of the multiple choice questions were conceptual. A few of the free response questions were conceptual in nature, but the majority of the questions were mathematical. Partial credit was awarded on mathematical questions.

2.2.2 Spatial Abilities

It has been argued multiple times that spatial ability is composed of two or three sub skills. According to Piaget there are three levels of spatial ability. The first, involves visualizing objects in two dimensions from different locations. The second stage involves visualizing three dimensional from different perspectives. In the third stage people add the ability to visualize translation, rotation and reflection (Sorby, 2009).

Others have recognized two main categories of spatial ability. First, Spatial Visualization is the ability to visualize the movement of objects. Second, Spatial Orientation is ability to imagine the appearance of objects from different orientations (Hegarty & Waller, 2004).

As a result three instruments were chosen to measure a student's spatial abilities, The Mental Rotation Test, The Perspective Taking/Spatial Orientation Test, and the Paper Folding Test.

2.2.3 The Perspective Taking/Spatial Orientation Test

In order to test students two-dimensional skills, students completed the Perspective Taking/Spatial Orientation Test (Hegarty & Waller, 2004). On this test students are presented with a simple map of an area and then asked to imagine they are standing at a location on the map. To answer questions students are asked to point to a different location on the map Students were given five minutes to complete twelve questions and were not allowed to rotate the test manuals, or draw on the provided map.

2.2.4 Mental Rotation Test

Participants completed the Vandenberg Mental Rotation Test (Peters & Laeng, A Redrawn Vandenberg and Kuse Mental Rotations Test:, 1995) as a test of three-dimensional skills. On this test students view a depiction of a 3D target figure and four test figures. Their task is to determine which two of the four test figures are rotations of the target figure. They are allowed 3 minutes for each of two sections of the test, with 20 items per section.

2.2.5 Paper Folding

Finally, to evaluate student's grasp of rotation, translation, and reflection, students were asked to complete the paper folding test (Ekstrom, French, Harmon, & Derman, 1976). In this test students were shown a series of images representing the folding of a piece of paper. Finally, an image indicated a hole that was punched in the folded paper. Questions were answered by indicating which image provided matched how the paper would appear after being unfolded. Students are given three minutes on each of two sections containing ten questions.

3. PROCEDURE AND ANALYSIS

3.1 Procedure

All students were given all four of the evaluation instruments at the beginning of the school year and again at the end of the school year. The tests were given on separate days at the beginning of the class periods, all within a few days of each other. The spatial ability tests were administered as originally designed on a hardcopy paper exam. The Force Concept Inventory was administered via computer with Webassign.net©. The test was administered in a school computer lab with the student's regular teacher acting as a facilitator. Students had already completed a few assignments on webassign.net from the first chapter. As such, they were comfortable with the interface.

The students were not offered any bonus points for their participation. However, in some cases their scores were shared when they asked. At no time did students have access to the key or scored papers.

The spatial ability tests were scored by hand. The only test requiring interpretation (not multiple choice) was the Perspective Taking/Spatial Orientation Test. Although only one grader was used, this test was scored twice, once by granting full credit for being within the correct octant (±22.5°) of a circle and again as an absolute deviation from the correct angle as measured manually by a protractor. The two results were similar.

3.2 Pre-course Group Comparisons

Since I had two distinct groups of students, Advanced Placement (AP) and College Preparatory (CP), I thought it wise to compare each group's knowledge coming into the course. In Table 1 and Figure 1 the pretest averages (with uncertainty in the mean) are shown for each group. Also included is the p-value determined by comparing the AP and CP courses using a two tailed t-test. The average for all students together is shown as well.

Table 1: Pretest Comparison of AP and CP

	AP Physics Mean(%)†	Regular Physics Mean(%)†	P*
Force Concept (FCI)	33±3	21±1	<0.05
Perspective (PTSO)	73±8	63±5	>0.05
Mental Rotation (MRT)	51±7	39±5	>0.05
Paper Folding (PFT)	73±5	52±3	<0.05

*p value calculated as 2 tailed ttest of pretest scores from the two different courses.

†uncertainty is the standard uncertainty in the mean

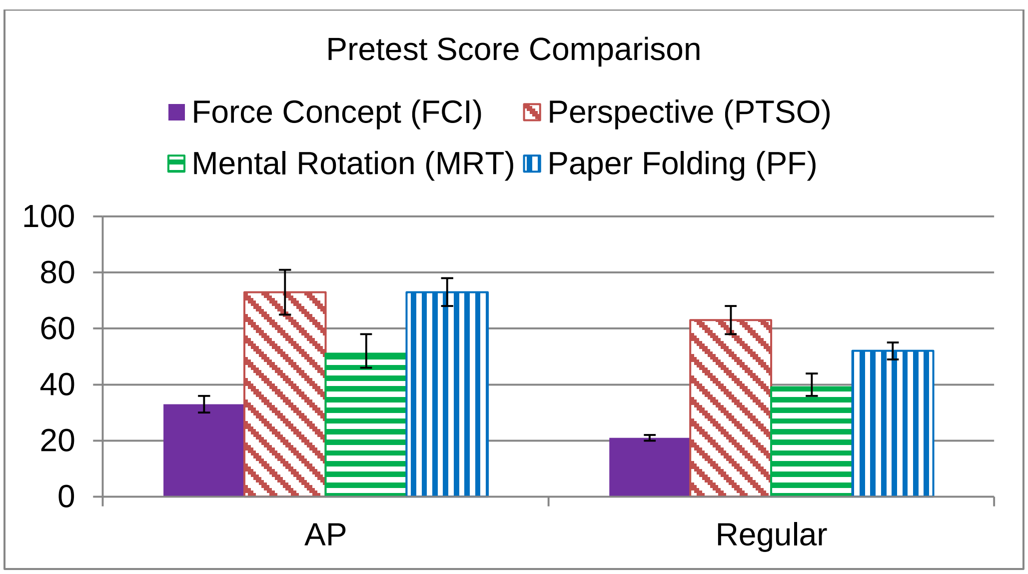

Figure 1: Pretest Score Comparison

The AP students statistically outscored the CP students on the Force Concept Inventory ($p<0.05$). AP students have, mostly, been in honors classes throughout high school. That includes honors physical science, where they would have studied Newtonian motion in more detail than their CP counterparts. We would also expect the honors students to maintain that information for longer.

I expected that all students would be approximately the same on measures of spatial ability. While this held true on the Perspective Taking Test and the Mental Rotation Test, the AP students did outscore the CP students on the Paper Folding Test by 4.3 questions on average (see Table 1). A histogram of the Paper Folding Pretests (Figure 2) shows that while the CP students were centered in the middle of the test, there were quite a few AP students for whom the test was not a challenge. Nine AP students scored 80% or better on the pretest. This would seem to indicate that my AP students came into Physics with both a better knowledge of Forces and Motion, and a measurably superior Spatial Ability as measured by the paper folding test.

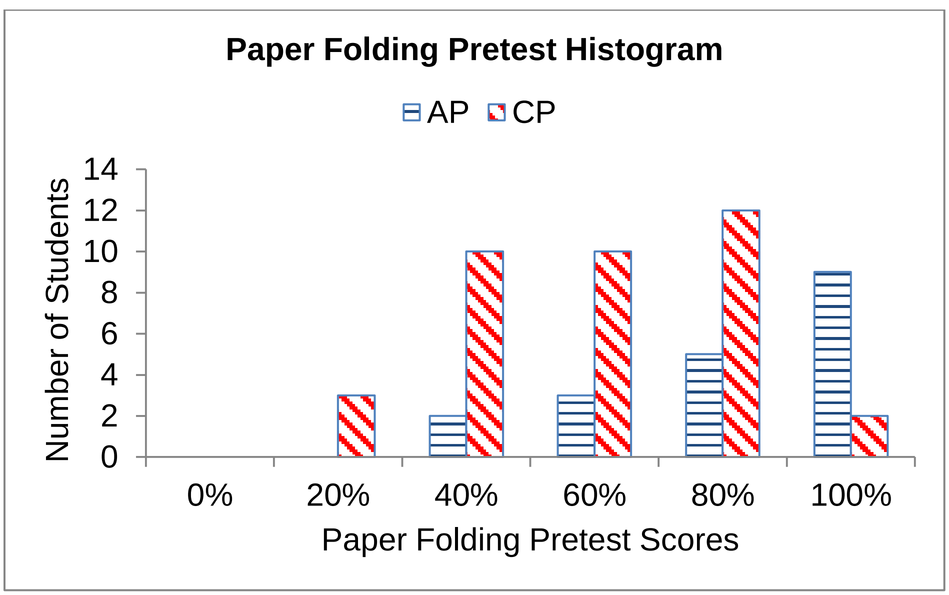

Figure 2: Paper Folding Pretest Histogram for AP and CP courses.

3.3 Does Physics Class Increase Students' Force Concept, or Spatial Abilities?

3.3.1 Force Concept Gain Caused by Course

In order to evaluate the effectiveness of the course and again to compare the AP course with the CP course, I compared the gain in the Force Concept Inventory (Table 2) to that of the group studied by Hestenes in the development of the FCI. In the development of the Force Concept Inventory Hestenes measured a pretest value of 41% for regular students and a 50% for honors students (Hestenes, Wells, & Swackhamer, 1992). This shows that both groups of our students came in below his with respect to Newtonian forces and motion. In addition Hestenes' measured gain was 21% for regular and 29% for honors. We also note in Table 2, that both groups came in below the gain seen by the Hestenes traditional instruction study group. Our regular course does not show any statistically significant gain over the period of the course. So we conclude that this AP course does cause an increase in students' Newtonian understanding of force and motion. However, we are inconclusive about the CP course's ability to raise students' understanding of Force and Motion.

Table 2: Force Concept Mean and Gain

	pre	Post	Gain	p
AP Physics (n=20)	33±3%	57±3%	23±3%	<0.05
Regular Physics (n=26)	21±1%	24±2%	3±3%	>0.05

- Gain is calculated as average of gains
- p is from two tailed ttest between pretest and posttest.
- Uncertainty is standard uncertainty in the mean

3.3.2 Perspective Taking / Spatial Orientation Test Gains.

Neither course's students showed statistically significant gains on the Perspective Taking/Spatial Orientation Test (PTSO). While we do show a gain of 0.9(8%) for the AP Course (Figure 3), this is not statistically significant (pretest/posttest p>0.05). The CP course shows little or no gain at all (0.03%, pretest/posttest p>0.05). This is probably the most surprising result of all. Because this test is so closely related to vector diagrams and free-body-diagrams, I expected there to be an increase in this skill as we taught them to draw and think using vectors. In the Pallrand paper (Pallrand & Seeber, 1984) it was found that college physics students did show gains in Spatial Orientation abilities as measured by the Card Rotation Test, and the Cube Comparison. However, this was at the college level and using a different measuring instrument.

One statistic that does deserve note is the decrease in the number of questions that students left blank on this timed test, (blanks were counted as incorrect). Students decreased from an average of 0.5 blank answers per student to 0.06 blank answers per student. This could indicate an increased comfort with the test itself as a result of having taken the pretest, or it could show that students increased in their comfort with this type of thinking.

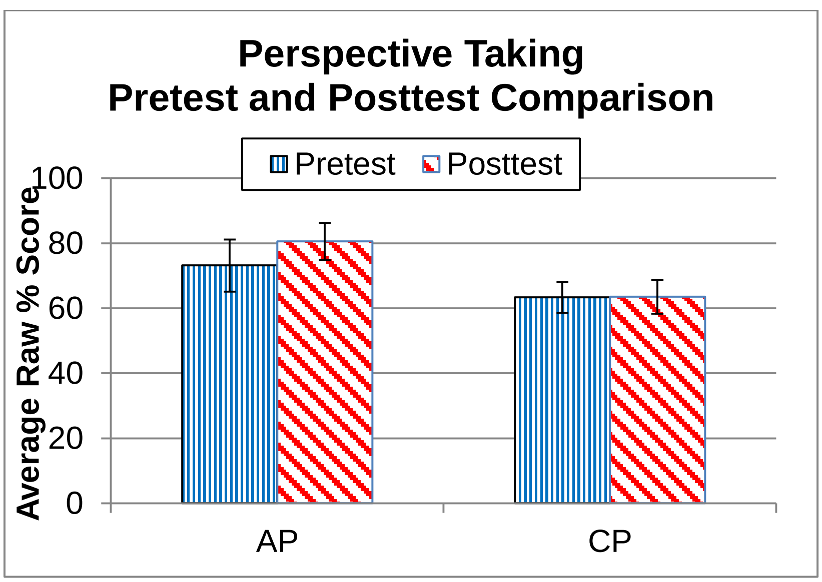

Figure 3: Average Raw % PTSO pre and post test scores

3.3.3 Mental Rotation Test Gains

Table 3: Mental Rotation Gains Summary

	Mental Rotation Test (MRT)			
	Pre(%)	Post(%)	Gain*(%)	p
AP Physics (n=17)	51±7	69±4	19±7	<0.05
Regular Physics (n=25)	39±5	26±6	-13±7	>0.05

* Gain is calculated as average of gains.
- p is calculated as the two tailed ttest of pretests and posttests.

Mental Rotation Test gains were only noticed in the AP course (Table 3). In fact there was a 19±7% increase in AP students' scores. This translates into getting four more questions (out of twenty) correct. This significance is further emphasized by the histogram of pre and post scores (Figure 4). Perhaps the most significant difference is noticed in the bottom of the pretest bell curve, as the worst two students improved significantly from their pretest scores.

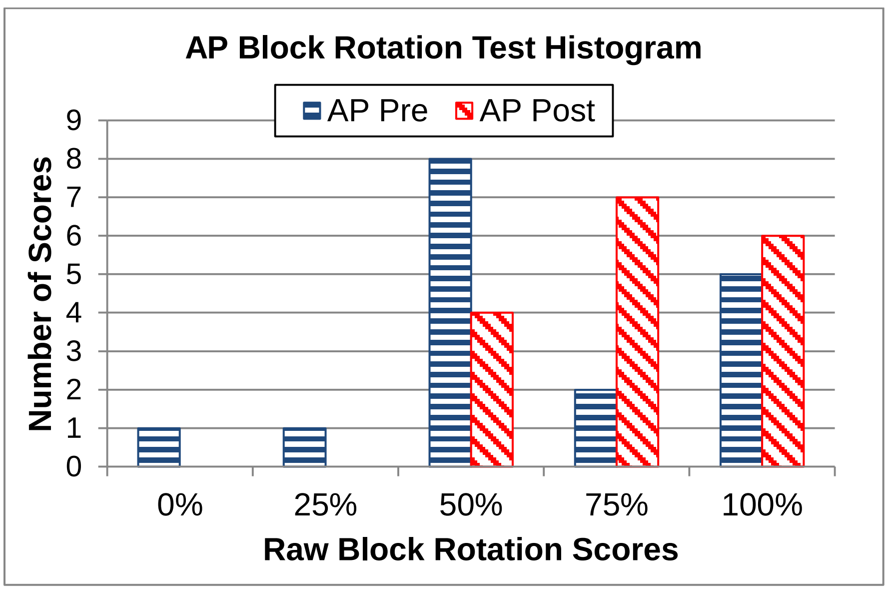

Figure 4: AP Mental Rotation Pre/Posttest Histogram

As emphasized in Figure 5, while there was only a small gain, the difference is statistically significant (pre/post p<0.05). In a resampling method (boot strapping) it was found that in 1000 random regroupings of my students where half of the students were considered, we saw a significant difference 20% of the time.

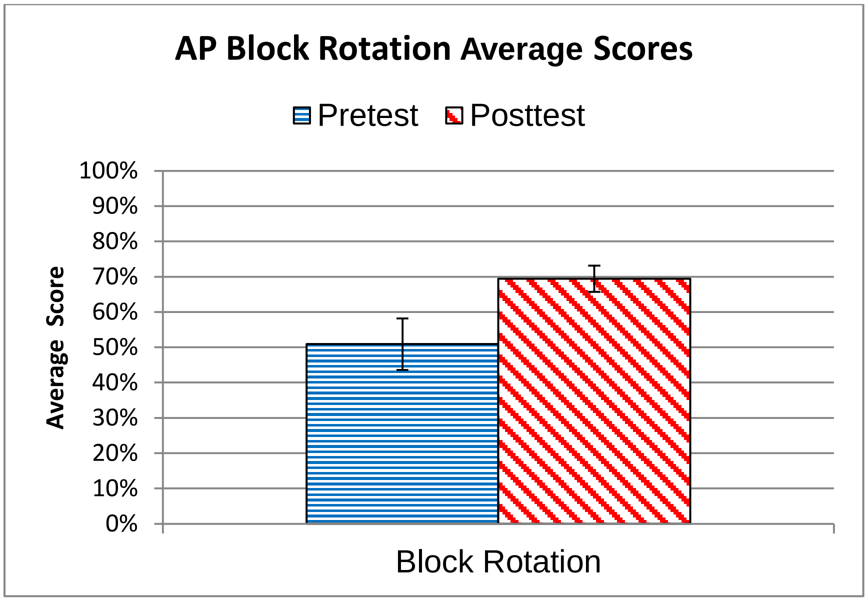

Figure 5: AP Mental Rotation Pre and Posttest Scores

3.3.4 Paper Folding Test Gains

Table 4: Paper Folding Pre and Post Test

	Paper Folding (PF) (%)			
	pre	Post	Gain	p
AP Physics (n=19)	74±4	76±4	3±4	>0.05
Regular Physics (n=37)	52±4	50±4	-3±4	>0.05

- Gain is calculated as average of gains.
- p is calculated with a two tailed ttest of pretests and posttests
- uncertainty: standard uncertainty in the mean

There were no significant gains in the paper folding test scores. (See summary on Table 4). The uncertainty in the mean for the gain was larger value of the gain itself. A t-test indicates no statistical difference between the pretest and posttest (p>0.05).

This wasn't too surprising considering there seems to be very little content in physics that is analogous to this test.

3.4 Do Better Force Conceptions or Spatial Abilities Enhance Performance in High School Physics?

The second question we sought to answer was whether a student's spatial ability reflected as enhanced performance in the course. In general there was no correlation between pretest scores and course test scores. To establish this, each pretest was correlated to test scores in the course using the Pearson Correlation Coefficient and the Spearman Rank Correlation (McDonald, 2009).

There was no statistically significant ($p>0.05$) relationship found on any measure of spatial ability (Table 5). Therefore, we cannot conclude that higher initial spatial abilities lead to increased course performance.

Although there does seem to be a correlation between the Force Concept Inventory pretest and the specific chapter test on forces in the AP course (Spearman Rho of 0.486 and $p<0.05$), the pretest scores on the Force Concept Inventory do not show statistically significant correlation to overall course performance ($p>0.05$). Therefore we cannot conclude that students coming in with higher conceptual understanding of forces and motion are at an advantage in the course, even if they do fair better than lower scoring peers on the one chapter test relating to forces.

Table 5: Pretest Correlation to Average Course Test Scores.

Instrument		AP mean	Regular Mean
Force Concept (FCI)	R	0.37	0.04
	p*	0.101	0.974
Perspective (PE)	R	0.24	-0.118
	p*	0.431	0.653
Block Rotation (BR)	R	0.297	-0.262
	p*	0.228	0.540
Paper Folding (PF)	R	0.357	0.012
	p*	0.053	0.711
* p is calculated using the Spearman Rank Correlation			

3.5 Gender Differences in Spatial Abilities

In a study of 103 college students Michael Peters, *et al.*, state that they did find a connection between gender and spatial abilities, but that the connection did not carry over to the performance in engineering courses (Peters, Chisholm, & Laeng, Spatial Ability, Student Gender, and Academic Performance, 1994). I found similar results. There was no statistical difference in genders on classroom test scores. However, the males outscored females on every Spatial Ability measure pretest ($p<0.05$) (Figure: 6).

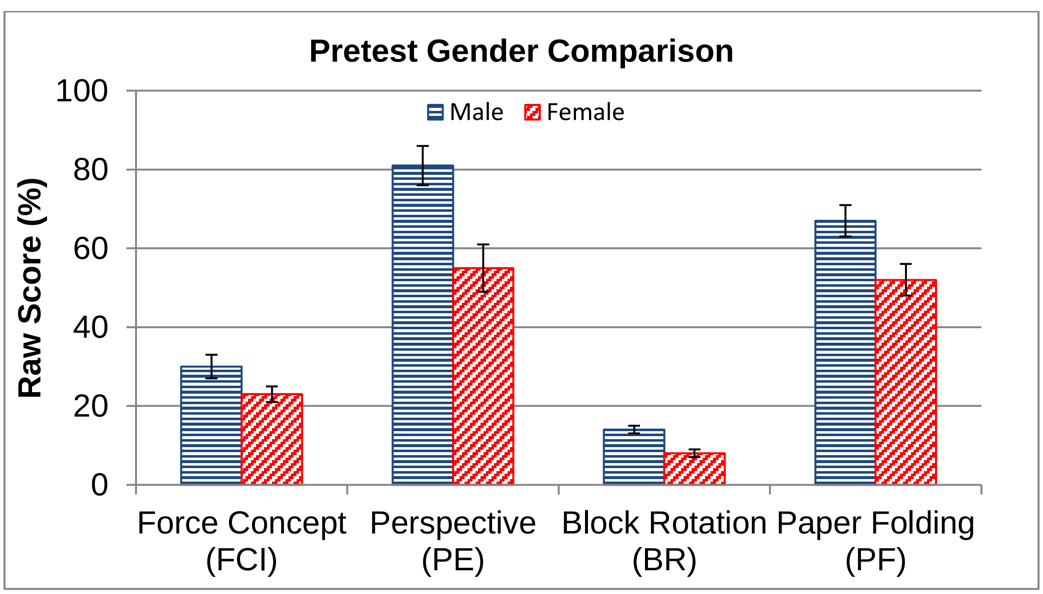

Figure: 6: Pretest Gender Comparison.

I did not see any gender differences in gains (Figure: 7). Although there was a significant difference between the gains of males and females on the Paper Folding Test, it came about mostly as a result of the loss shown in the male population. Neither gender's gain (nor loss) was shown to be statistically significant ($p>0.05$ for pretest to posttest comparison). Therefore, the difference between genders on this test seems to be trivial.

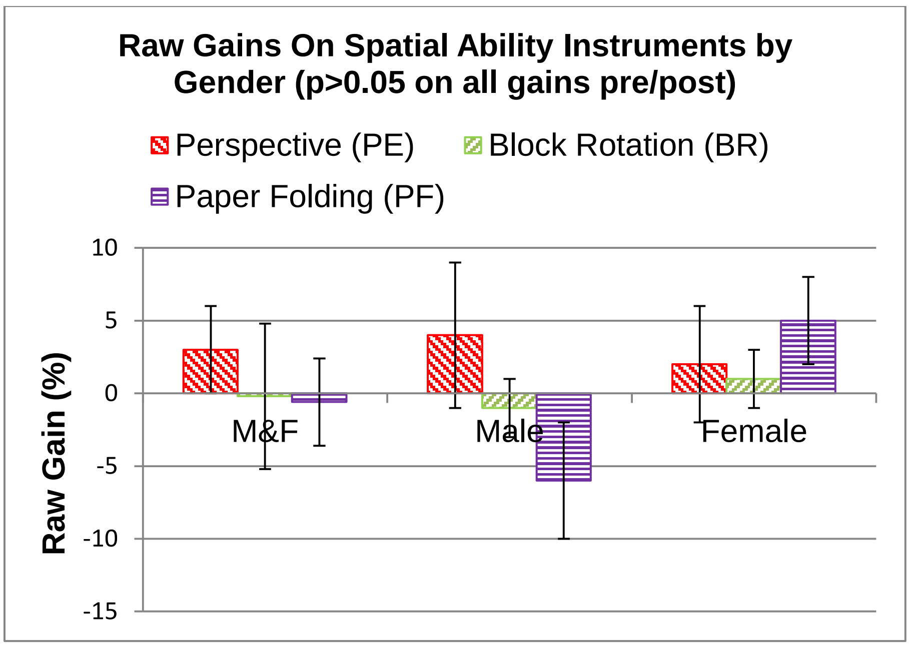

Figure: 7: Raw Gains on Spatial Ability Instruments, by Gender.

In general males came to the course with higher spatial abilities and higher force concept abilities. However, this difference did not cause them to outperform the girls in the course.

4. SUMMARY AND CONCLUSIONS

In general I did not find significant relationship between spatial ability and performance in high school physics. The AP course did possibly show an ability to increase a student's spatial abilities as measured by the Mental Rotation Test, but failed to cause significant increases in any of the other spatial ability measures. I find this a little surprising since the Perspective Taking/Spatial Orientation test seems to fit the content of physics better than the other spatial abilities tests. I find it entirely plausible that the lack of results is related to two main aspects of my study. First, the only course that showed increases in Force Concepts was the AP course and it only consisted of twenty students. Second, I feel that by waiting until the last days of school, senioritis may have kicked in and increases may have been hidden by student apathy. If the study was repeated for larger numbers of students, the posttest was given earlier in the year, and performance on the tests was somehow tied to student grades, I feel that the results may come out to show a more significant correlation.

I also find it interesting that my own subjective analysis of students that were more natural at understanding the course correlated well with the overall spatial abilities average score. That is, the students that I would have called "naturals" after a few weeks in class were the very ones who had the highest overall averages on the spatial abilities tests. One student in particular, who scored the highest overall average on the spatial ability tests, was the very student who would get it first and then help me tutor other students as we worked on assignments. However, his overall test grade does not reflect this because he never felt the need to study for tests.

I can also name two external factors that may have diluted my results. First, a student's individual drive would offset an initial deficiency in spatial skills or force concepts. One particular student, started at the bottom third of spatial ability, but had the highest test score because her idea of a successful grade is nothing less than perfection. Secondly, I feel that I may have, unintentionally, skewed results as I paid extra attention to students who struggled with the material. This may have flattened the results by raising the lower students test scores without necessarily increasing their spatial abilities.

Also, it should be noted that these particular instruments may not have been the best fit for my study. On two of the instruments, Perspective Taking (PTSO), and Paper Folding (PFT), both groups of students scored above 50% (Table 1). My AP students scored above 50% on all spatial ability pretests, and scored 73% on two of them. This indicates that my chosen tests may have been below the level of my students. While the Mental Rotation Test (MRT) did seem to challenge them, I would rather replace the other two tests with something more on level to the development of my students.

Despite the limitations of this study, the results still allow us to see a hint of a relationship between spatial ability and high school physics. Specifically that high school physics may increase spatial ability as measured by the Mental Rotation Test. Further study, with larger populations, and better fitting instruments, may lead to a more significant finding.

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APPENDIX

Application for Exemption from Institutional Oversight

Institutional Review Board
Dr. Robert Mathews, Chair
131 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.6792
irb@lsu.edu
lsu.edu/irb

Unless qualified as meeting the specific criteria for exemption from Institutional Review Board (IRB) oversight, ALL LSU research/projects using living humans as subjects, or samples, or data obtained from humans, directly or indirectly, with or without their consent, must be approved or exempted in advance by the LSU IRB. This Form helps the PI determine if a project may be exempted, and is used to request an exemption.

– Applicant, Please fill out the application in its entirety and include the completed application as well as parts A-E, listed below, when submitting to the IRB. Once the application is completed, please submit two copies of the completed application to the IRB Office or to a member of the Human Subjects Screening Committee. Members of this committee can be found at http://www.lsu.edu/screeningmembers.shtml

– A Complete Application Includes All of the Following:

(A) Two copies of this completed form and two copies of part B thru E.
(B) A brief project description (adequate to evaluate risks to subjects and to explain your responses to Parts 1&2)
(C) Copies of all instruments to be used.
*If this proposal is part of a grant proposal, include a copy of the proposal and all recruitment material.
(D) The consent form that you will use in the study (see part 3 for more information.)
(E) Certificate of Completion of Human Subjects Protection Training for all personnel involved in the project, including students who are involved with testing or handling data, unless already on file with the IRB. Training link: (http://phrp.nihtraining.com/users/login.php.)
(F) IRB Security of Data Agreement: (http://www.lsu.edu/irb/IRB%20Security%20of%20Data.pdf)

1) Principal Investigator: Dana Browne **Rank:** Professor

Dept: Physics **Ph:** (225) 578-6843 **E-mail:** browne@phys.lsu.edu

2) Co Investigator(s): please include department, rank, phone and e-mail for each

Shawn Milner
Graduate Student
225-278-8678
milner2@lsu.edu

IRB# [illegible] LSU Proposal # [illegible]
(X) Complete Application
(X) Human Subjects Training

3) Project Title: Investigation of Connections between Spatial Abilities and High School Science Courses

Study Exempted By:
Dr. Robert C. Mathews, Chairman
Institutional Review Board
Louisiana State University
203 B-1 David Boyd Hall
225-578-8692 | www.lsu.edu/irb
Exemption Expires: [illegible]

4) Proposal? (yes or no) no **If Yes, LSU Proposal Number**

Also, if YES, either
◯ **This application completely matches the scope of work in the grant**
OR
◯ **More IRB Applications will be filed later**

5) Subject pool (e.g. Psychology students) High School Students in Baton Rouge, LA

*Circle any "**vulnerable populations**" **to be used:** (children <18; the mentally impaired, pregnant women, the ages, other). Projects with incarcerated persons cannot be exempted.

6) PI Signature [signature] **Date** 6/30/11 (no per signatures)

** **I certify my responses are accurate and complete.** If the project scope or design is later changes, I will resubmit for review. I will obtain written approval from the Authorized Representative of all non-LSU institutions in which the study is conducted. I also understand that it is my responsibility to maintain copies of all consent forms at LSU for three years after completion of the study. If I leave LSU before that time the consent forms should be preserved in the Departmental Office.

Screening Committee Action: Exempted [illegible] Not Exempted ____ Category/Paragraph [illegible]

Reviewer [illegible] **Signature** [signature] **Date** [illegible]

VITA

Michael Shawn Liner was born to James and Violet Liner in February 1971 in West Monroe, LA. He attended elementary, middle, and high school in Ouachita Parish and graduated from West Monroe High School in 1989. The following fall he entered Louisiana State University in Baton Rouge, LA, where he earned a Bachelor of Science in Petroleum Engineering in 1995. He entered Louisiana State University Graduate School in June 2010 and is a candidate for the Masters of Natural Science degree. He is currently teaching Physics, Chemistry, and Engineering at Parkview Baptist School in Baton Rouge, LA, while also teaching Physics at Louisiana Virtual School, headquartered in Baton Rouge, LA.