# Work in Progress: Assessing the Impact of Spatial Skills on Performance in a Statics Course

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## Abstract

Spatial ability is broadly defined as an understanding of spatial relations and an ability to mentally transform visual information. Much work has been done to show the correlation between students' spatial ability and their academic performance in STEM fields. Further work has also linked spatial ability to professional achievements in STEM areas and shown that spatial ability can be taught and retained through targeted interventions.

One area of engineering education where spatial content is particularly prevalent is engineering mechanics. This work specifically examines performance in a statics course taught primarily to sophomore undergraduate students. Examples of spatial content students are required to understand to perform well in a statics course include three-dimensional vectors, free body diagrams, equivalent force systems, and machines.

This paper explores the relationship between students' performance on several spatial ability assessments and their scores on exams through multiple regression models as seen in a western university. Additionally, this research exams the relationship between spatial ability and concept focused questions from the exams. Spatial ability assessments utilized in this work include the Mental Cutting Test (MCT) and the Purdue Spatial Visualization Test: Rotations (PSVT:R) which measure spatial ability constructs of mental rotation, proportional reasoning, and cross-sectional visualization. Results of the study will indicate specific topics within a statics course that require significant spatial ability to succeed. This understanding will allow engineering educators to prepare spatial interventions before students are exposed to difficult spatial problems and provide meaningful feedback on tasks that involve spatial skills.


## Introduction

There is a significant body of research that indicates a correlation between spatial ability and success in STEM fields [1], [2]. Specific studies have determined correlations between spatial ability and medical sciences [3], computer drafting [4], chemistry [5], and calculus [6]. Within engineering, spatial ability has been correlated to academic performance, retention rates, and professional success[5], [7]. This correlation has led to an interest in developing and training spatial ability in engineering students.

Over the years, several spatial ability training courses have been developed. Many of these courses offer spatial training as a supplemental or required aspect of intro-level engineering curriculum. Spatial ability trainings typically include activities involving 2D and 3D sketching, object rotation, scaling exercise, and object manipulation [5], [6]. A meta-analysis conducted by Uttal, Miller, and Newcomb determined that spatial training is effective, lasting, and transferable [1]. Recently, virtual reality has been utilized to develop spatial training programs [8], [9], [10]. Virtual reality programs have similar tasks as those of traditional spatial ability training programs, however, they allow the user to more easily interact with the material. Virtual reality training programs have been shown to be effective, especially for students with initially low levels of spatial ability [8].

There is evidence that engineering mechanics classes improve spatial thinking skills in undergraduate engineering students [7]. A study conducted by Wood, Goodridge, Call, and Sweeten determined that an engineering statics course, the first course in a typical engineering mechanics series, significantly improved spatial ability in engineering students [7]. Furthermore, proficiency in the statics concepts of shear and bending diagrams, vectors, and complex free body diagrams have been correlated with spatial ability [8]. However, research on the correlation between the understanding of engineering mechanics concepts and spatial ability is still limited.

Spatial ability is a mental construct that encompasses the skill of visualizing and manipulating 2D and 3D objects in one's mind. There are many aspects of spatial ability, however this paper specifically evaluates the constructs of mental rotation and transformation. In this study, spatial ability was measured using the Mental Cutting Test (MCT) [11] and the Purdue Spatial Visualization test: Rotation (PSVT:R) [12]. The MCT evaluates the cross-section visualization and proportional reasoning aspect of spatial ability. The PSVT:R evaluates mental rotation aspects of spatial ability.

The MCT was developed as part of a college entrance exam [11]. The test consists of 25 questions and has a time limit of 20 minutes. Each problem presents the participant with a 2D isometric drawing of a 3D figure which is cut by an imaginary plane included in the drawing. Participants are then required to determine the cross-sectional shape that would be revealed by cutting the 3D object where the plane intersects the object. [13]. Figure 1 depicts a typical MCT question.

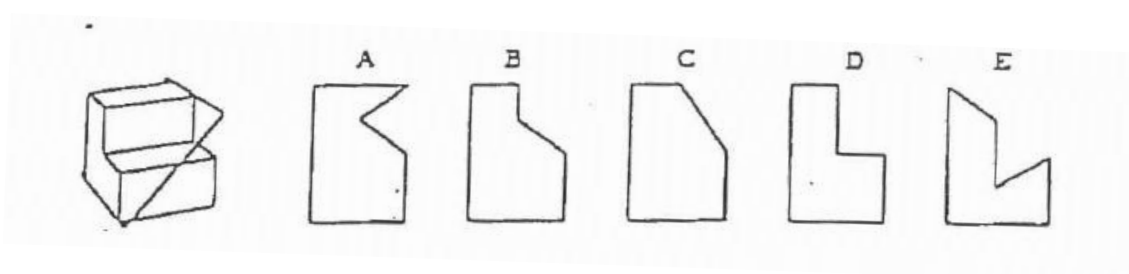



**Figure 1. Example problem from the MCT**

The PSVT:R consists of 30 questions with a typical time limit of 20 min [12]. The PSVT:R first requires participants to analyze two images of the same figure. The first image is a 2D isometric drawing of a 3D shape in an "original" orientation. The second image is the same shape but rotated in one or more directions. The participant is then provided an image of a second figure in an original orientation and five options of the figure rotated in several ways. The participant is asked to selected the rotated option that matches the rotation of the first set of figures. [13]. Figure 2 depicts a typical test question of the PSVT: R.

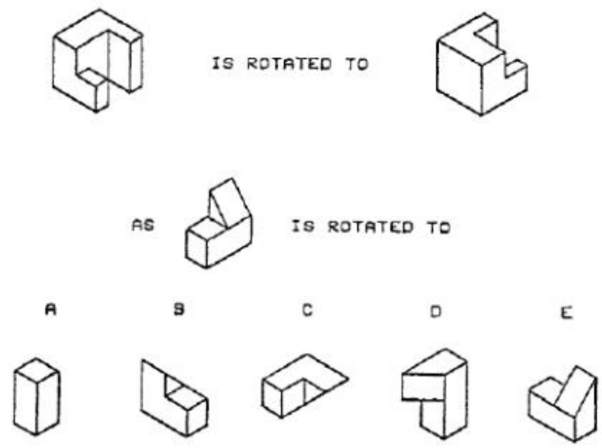



**Figure 2. Example problem from the PSVT:R (Guay, 1976)**

This research further investigates how students' performance on exams and quizzes in a statics course is correlated with their performance on the MCT and PSVT:R. By understanding which specific concepts require high levels of spatial ability, preventative spatial training can be implemented prior to introducing the topic in the course. The following research questions guided this work.

RQ1: Is there a correlation between exam performance in statics and spatial ability as measured on the PSVT:R and MCT?
RQ2: Is there a correlation between quiz performance in statics and spatial ability as measured on the PSVT:R and MCT.
RQ3: Is there a correlation between individual exam problems in statics and spatial ability as measured on the PSVT:R and MCT.

**Population**

The population used for this study comprised of mainly second year engineering students at a college in the western United States enrolled in the Engineering Mechanics: Statics course. The statics class is comprised primarily of civil, environmental, mechanical, and biological engineering students. Typically, students take calculus, physics, chemistry, and drafting concurrent with the statics course. Exam performance data was collected from the spring and fall semesters in 2016 and the spring semester in 2017. Quiz score data was collected from the spring 2017 semester. Exam problem data was collected from the spring semesters in 2016 and 2017.

**Methods**

This study focuses on how students' spatial ability is correlated with performance scores on statics exams, quizzes, and individual exam items. In this way, the impact of spatial skills can be evaluated in both broad and specific applications.

As part of the class curriculum, students were required to take the MCT and PSVT:R during the first and last week of the 15-week course. Students took three midterm exams spaced throughout the semester. The concepts covered in the three midterm exams is described in Table 1. Quizzes were given weekly throughout the 15-week course, and each quiz covered fewer but more in-depth topics, described in Table 2. The instructor was the same in these different courses and all curricular elements was identical.

**Table 1. List of Exam Topics**

| Exam | Topics Tested |
|---|---|
| Exam 1 | 2D and 3D vectors<br>Free body diagrams |
| Exam 2 | 2D and 3D reactions<br>Truss analysis<br>Frames and machines |
| Exam 3 | Shear and bending diagrams and calculations<br>Friction |

**Table 2. List of Quiz Topics**

| Quiz | Topics Tested |
|---|---|
| Quiz 2 | Math and Physics review |
| Quiz 3 | Equilibrium<br>Free body Diagrams<br>Moments |
| Quiz 4 | Moment couples<br>Equivalent forces<br>Distributed loading |
| Quiz 5 | 2D equilibrium<br>2-force members |
| Quiz 6 | Truss analysis |
| Quiz 8 | Shear and moment diagrams |
| Quiz 9 | Friction |
| Quiz 10 | Center of gravity<br>Centroid locations<br>Composite bodies |
| Quiz 11 | Fluid pressure<br>Moments of inertia |

For the exam correlation and to answer RQ1, three semesters of anonymized class scores were analyzed comprising 259 students. The data included pre-and-post scores of the MCT and PSVT: R, and raw exam scores (before curving or extra-credit was factored in). The pre scores, post scores, and test scores from the multiple semesters were compiled and missing data was removed. Normality of each dataset was then calculated. The correlations between all the datasets were calculated using the Spearman-Rho model. The correlation coefficients were used to determine if the exam scores were significantly correlated to the scores on the spatial ability assessments.

For the quiz correlations and to answer RQ2, data from the spring 2017 semester was used, and comprised of 80 students. The data included the pre and post MCT and PSVT:R scores from the spring 2017 semester and data from the nine quizzes given that semester. The normality of each data set was calculated and then correlations between the data sets were calculated using the Spearman-Rho model. Data from other semesters were missing information about the concepts tested in each quiz and were not included in this analysis.

The third part of this study measured the correlation between individual exam problems and spatial ability assessment scores or RQ3. For this part of the study, answers from a total of 120 exam questions were recorded. The questions came from six exams given in the spring semester of 2016 and 2017. Each exam comprised of 20 questions and had a 3 hr time limit. Unanswered questions were marked blank and later removed from the dataset. Answers were then converted to a binary system of correct/incorrect. The Spearman-Rho model was used to find correlations between spatial ability scores and performance on individual exam items.

## Data Analysis

All data analysis was completed in MS Excel and Jamovi 2.3.28 [14]. The first step in the data analysis was calculating the normality of each dataset. Normality was calculated using the Sharpio-Wilk test and each dataset was found to deviate significantly from a normal distribution. Normality of each pre-spatial test scores, post-spatial test scores, exam scores, and quiz scores were calculated separately.

Next, correlation coefficients were calculated between each dataset. The Spearman-Rho regression model was used to calculate the correlation coefficient (r) since all the datasets were skewed. A correlation matrix was generated in Jamovi to calculate and compare the correlations between the datasets.

## Results

The Spearman-Rho correlation coefficients between student performance on spatial exams and Exams 1, 2, and 3 ranged from 0.158 to 0.474, answering RQ1. All the correlations were statistically significant ($p < 0.05$) and the exam correlation results can be found in Table 3. The highest correlation coefficients were observed between exam 2 and the pre and post PSVT:R scores. The lowest correlation coefficients were observed between exam 3 and the post-MCT score.

**Table 3. Exam Correlation Coefficients**

| | Pre-MCT | | Pre-PSVT:R | | Post-MCT | | Post-PSVT:R | |
|---|---|---|---|---|---|---|---|---|
| Exam 1 | r | 0.386 | r | 0.457 | r | 0.393 | r | 0.437 |
| | p-val | < .001 | p-val | < .001 | p-val | < .001 | p-val | < .001 |
| | n | 248 | n | 248 | n | 209 | n | 210 |
| Exam 2 | r | 0.364 | r | 0.467 | r | 0.378 | r | 0.474 |
| | p-val | < .001 | p-val | < .001 | p-val | < .001 | p-val | < .001 |
| | n | 248 | n | 248 | n | 210 | n | 209 |
| Exam 3 | r | 0.264 | r | 0.255 | r | 0.158 | r | 0.266 |
| | p-val | < .001 | p-val | < .001 | p-val | < .001 | p-val | 0.022 |
| | n | 246 | n | 246 | n | 210 | n | 209 |

The Spearman-Rho correlation coefficients between spatial exam scores and quiz scores had a similar range of 0.023 to 0.457 answering RQ2. Only 16 of the 36 relationships were statistically significant. Quiz 4 (moment couples) and quiz 9 (friction) had the highest correlation with spatial exam performance. The results for the quiz score correlations are displayed in Table 4.

**Table 4. Quiz Correlation Coefficients**

| | **Pre-MCT** | | **Pre-PSVT:R** | | **Post-MCT** | | **Post-PSVT:R** | |
|---|---|---|---|---|---|---|---|---|
| Quiz 2 | r | 0.134 | r | 0.266 | r | 0.159 | r | 0.122 |
| | p-val | 0.263 | p-val | 0.024** | p-val | 0.198 | p-val | 0.32 |
| | n | 72 | n | 72 | n | 67 | n | 68 |
| Quiz 3 | r | 0.046 | r | 0.032 | r | 0.076 | r | 0.091 |
| | p-val | 0.696 | p-val | 0.785 | p-val | 0.531 | p-val | 0.449 |
| | n | 76 | n | 76 | n | 70 | n | 71 |
| Quiz 4 | r | 0.266 | r | 0.401 | r | 0.243 | r | 0.264 |
| | p-val | 0.022** | p-val | < .001** | p-val | 0.044** | p-val | 0.027** |
| | n | 74 | n | 74 | n | 69 | n | 70 |
| Quiz 5 | r | 0.023 | r | 0.269 | r | 0.108 | r | 0.121 |
| | p-val | 0.847 | p-val | 0.021** | p-val | 0.377 | p-val | 0.317 |
| | n | 73 | n | 73 | n | 69 | n | 70 |
| Quiz 6 | r | 0.236 | r | 0.361 | r | 0.36 | r | 0.342 |
| | p-val | 0.058 | p-val | 0.003** | p-val | 0.004** | p-val | 0.006** |
| | n | 65 | n | 65 | n | 61 | n | 62 |
| Quiz 8 | r | 0.196 | r | 0.308 | r | 0.222 | r | 0.206 |
| | p-val | 0.097 | p-val | 0.008** | p-val | 0.067 | p-val | 0.087 |
| | n | 73 | n | 73 | n | 69 | n | 70 |
| Quiz 9 | r | 0.451 | r | 0.457 | r | 0.361 | r | 0.359 |
| | p-val | < .001** | p-val | < .001** | p-val | 0.003** | p-val | 0.002** |
| | n | 71 | n | 71 | n | 68 | n | 69 |
| Quiz 10 | r | 0.075 | r | 0.343 | r | 0.145 | r | 0.356 |
| | p-val | 0.527 | p-val | 0.003** | p-val | 0.232 | p-val | 0.002** |
| | n | 74 | n | 74 | n | 70 | n | 71 |
| Quiz 11 | r | 0.295 | r | 0.16 | r | 0.121 | r | 0.118 |
| | p-val | 0.015** | p-val | 0.192 | p-val | 0.333 | p-val | 0.34 |
| | n | 68 | n | 68 | n | 66 | n | 67 |

**Indicates p-value <0.05

Spearman-Rho correlation coefficients were calculated for 120 exam problems; 37 problems had a statistically significant correlation to at least 1 spatial ability test and 19 problems had significant correlations to multiple spatial ability tests. The correlation coefficients ranged from -0.437 to 0.603 answering RQ3. The highest correlation (r=0.603) was between an exam 2 problem the the post-PSVT:R spatial exam. The lowest correlation (r=-0.437) was between exam 1 problem and the pre-PSVT:R spatial exam. Thirteen of the problems were moderately correlated to a spatial exam with r values ranging from 0.401 to 0.603 as shown in Table 5.

**Table 5. Moderatly Correlated Exam Problems and Topics**

| Problem ID | Topic | pre-MCT | pre-PSVT:R | post-MCT | post-PSVT:R |
|---|---|---|---|---|---|
| Sp16-T3-11 | Bending Moment (Conceptual) | | r=0.417 | | |
| Sp16-T1-5 | Vector (3D) | | | r=0.425 | |
| Sp16-T1-9 | Vector (conceptual) | | | r=0.429 | |
| Sp16-T3-2 | 2D Reactions | | | r=0.401 | |
| Sp16-T3-15 | Friction | | | r=0.401 | |
| Sp16-T4-8 | Hydrostatic Resultant Force | | | r=0.403 | |
| Sp17-T3-11 | Bending Moment (equation generation) | | | r=0.428 | |
| Sp17-T4-15 | Hydrostatic Resultant Force | | | r=0.408 | |
| Sp16-T1-10 | 2D Reactions | | | | r=0.408 |
| Sp16-T1-11 | 2D reactions | | | | r=0.408 |
| Sp16-T2-3 | 3D Reactions | | | | r=0.459 |
| Sp16-T2-9 | Truss Analysis | | | | r=0.603 |
| Sp16-T2-19 | Machine Analysis | | | | r=0.402 |

Additional description of the 13 moderately correlated exam problems are listed below.

- Sp16-T3-11 required students to calculate the bending moment magnitude at a hinge on a beam with a fixed and rolling reaction. The beam was subjected to a moment, point, and distributed load.
- Sp16-T1-5 provided students with a drawing of a set of 3D vectors and required the students to calculate the angle between two of the vectors.
- Sp16-T1-9 was a conceptual question that required students to understand the definition of a unit vector.
- Sp16-T3-2 required students to calculate the force present on a bent rod at a collared support.
- Sp16-T3-15 required students to calculate the force required to cause a large drum to slip. The force was applied to the drum at a downward angle.
- Sp16-T4-8 required students to calculate the resultant hydrostatic force on a planar surface.
- Sp17-T3-11 required students to develop a moment equation for a simply supported beam with a triangular distributed load.
- Sp17-T4-15 required students to calculate the horizontal resultant force on a curved surface of a dam.

- Sp16-T1-10 required students to calculate the resultant force magnitude acting on a cantilever beam subjected to an angled point load and triangular load.
- Sp16-T1-11 required students to determine the angle of the resultant force from previous problem.
- Sp16-T2-3 provided students with a 3D drawing of a bar with 6 reactions experiencing a single point load. Students were required to calculate the reactionary force at on the of the reactions.
- Sp16-T2-9 provided students with a drawing of an internal truss of an airplane wing and required the students to calculate the force in one of the truss members.
- Sp16-T2-19 required students to calculate the force acting on a hydraulic cylinder in a simple boom lift diagram.

**Discussion**

Correlation coefficients were interpreted based on the Dancey Reidy values [15]. Table 4 lists the interpretations used in this paper.

**Table 4. Interpretation of Correlation values**

| Correlation Value | Interpretation |
|---|---|
| ± 1 | Perfect |
| ± 0.9 - 0.7 | Strong |
| ± 0.6 - 0.4 | Moderate |
| ±0.3 - 0.1 | Weak |

Exam 1 has moderate correlation to the pre and post PSVT:R spatial scores and a weak correlation to the pre and post MCT scores. Exam 1 tests 2D and 3D vectors and simple-to-complex free body diagrams (FBD). Most vector problems require mental rotation to adequately understand the physical meaning behind manipulations. FBD requires the use of proportional reasoning and rotation to determine how varied distances between objects and forces affect the system. Exam 2 also has a moderate correlation to the pre and post PSVT:R spatial scores and is weakly correlated to the pre and post MCT scores. Exam 2 covers concepts of 2D and 3D reactions, truss analysis, and frames and machine problems. Solving 2D and 3D reactions involves using moments, which is a rotational based spatial skill. Frames and machine problems also use rotation and an understanding of how the forces apply to the moving parts and transfer through parts. Exam 3 was weakly correlated to all four spatial ability exams with the highest correlation occurring between exam 3 and the post MCT ($r= 2.66$). Exam 3 covers the topics of shear and bending diagrams/calculations and friction.

The correlation of exams 1 and 2 with the PSVT:R supports the inclusion of spatial training early in the semester/engineering curriculum, especially on the topic of mental rotation. The low correlations to exam 3 might be indicative of students having developed test taking skills by this point in the semester since research shows that the topics of shear and bending diagrams require spatial ability [11], [12].

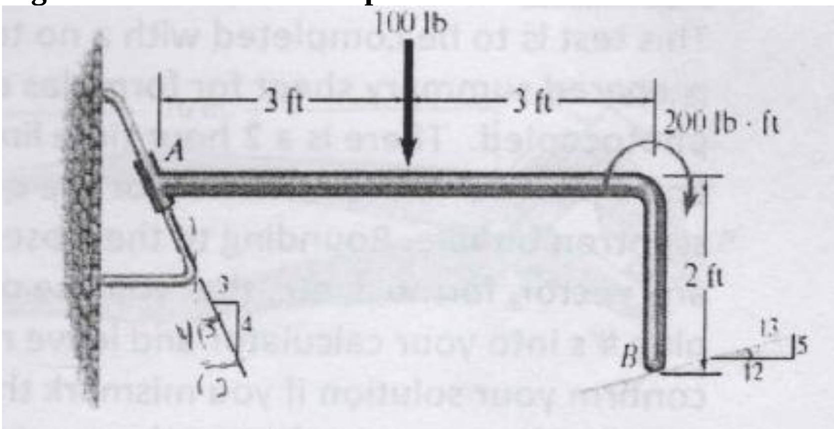
Of the 9 quizzes analyzed, only 2 quizzes exhibited moderate correlation. Quiz 4, which tested moment couples and equivalent forces, had a moderate correlation (r=0.401) to the pre-PSVT:R and was weakly correlated to the other 3 spatial tests. The moderate correlation supports the relationship between spatial ability, especially the spatial construct of rotation, and moment couples/equivalent forces. This relationship is also supported by moderate correlations to exam 2, which tests moment couples and equivalent forces among other topics. The high correlation supports spatial intervention prior to introducing moment couples. Types of intervention could include a hands on activity with a 3D modeled system of moment of a couple, or in class displayed of tire jacks or steering wheel.

Quiz 9 which tested friction, was moderately correlated with the pre-MCT (r=0.451) and pre-PSVT:R (r=0.457) and weakly correlated with the post MCT and PSVT:R. The high correlation between quiz 9 and the PSVT:R is inconsistent with the low correlation of exam 3 with the rotational spatial ability exam. However, the relationship between spatial scores and friction is not unexpected. Friction problems required students understand governing situations and to solve both slipping and tipping (rotating cases) and then select the governing solution. Solving a tipping case not only requires students to determine if the object rotates, but they also must locate the pivot point and where the forces act on the body. The moderate correlation for both the MCT and PSVT:R supports the relationship between friction problems and spatial ability. It would likely benefit students to conduct some spatial training prior to the topic of friction being introduced. A spatial intervention could be an in-class or virtual tip-slip demonstration. Additionally, the high correlation between the friction problems and spatial scores supports the idea of students' improved test taking skills and less reliance on intuitive spatial ability to pass the exam.

Of the 37 exam problems with statistically significant correlations with spatial performance, 13 were moderately correlated to a spatial ability test. Seven problems had moderate correlations with the post-MCT, one problem was moderately correlated with the pre-PSVT:R, and five problems were moderately correlated with the post-PSVTR. Recurring topics represented in these problems include 2D and 3D reactions, vectors, bending moments, and hydrostatic resultant forces.

Four of the thirteen exam problems with a moderate correlation to spatial performance involve students solving 2D and 3D reactions. Three of the four problems were correlated with the post-PSVT:R spatial ability test and the remaining problem was related to the post-MCT. Figures 3-6 display the 4 problems. Sp16-T1-10 and Sp16-T1-11 were related problems that required students to solve Sp16-T1-10 prior to solving Sp16-T1-11. The identical correlation coefficient indicates that if students correctly solved Sp16-T1-10, they also correctly solved Sp16-T1-11. The relationship between 2D and 3D reaction problems and spatial ability aligns with the results from the exam and quiz analysis. The topic of reactions is specifically tested in exam 2 and quiz 4, both of which displayed moderate correlations to the pre-PSVT:R exam. This data supports the importance of student's spatial ability to correctly solve 2D and 3D reactions in a FBD.

**Figure 3. Exam Problem Sp16-T3-2**

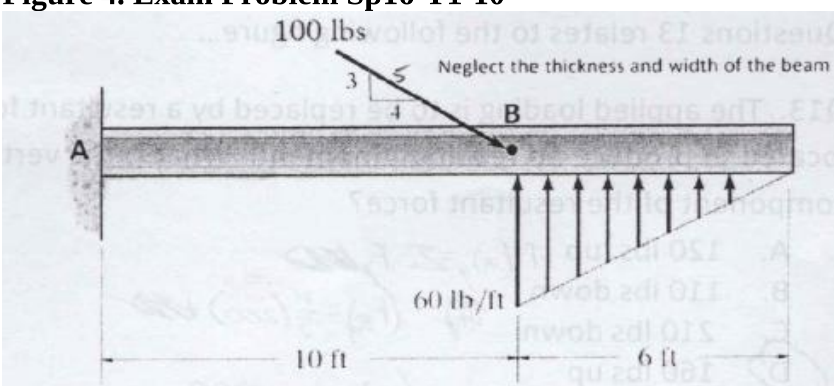



Q: What is the force present on the bent rod at the support A?

A) 40 lbs
B) 86 lbs
C) 26 lbs
D) 98 lbs
E) 115 lbs

The correct answer is A

**Figure 4. Exam Problem Sp16-T1-10**

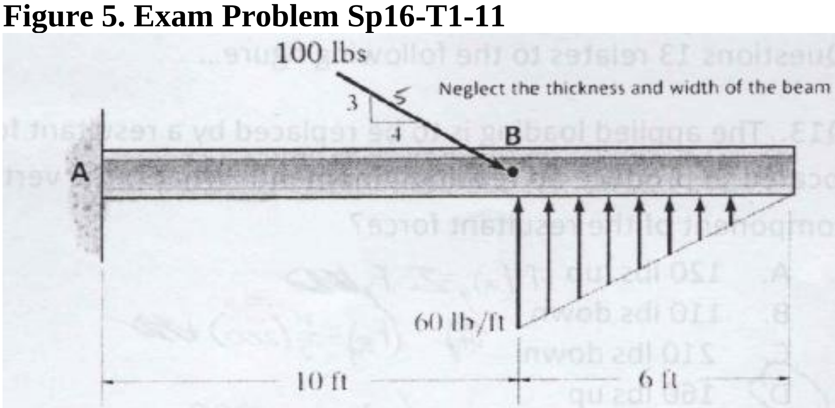



Q: What is the resultant force magnitude given the applied loading shown?

A) 120 lbs
B) 176 lbs
C) 212 lbs
D) 96 lbs
E) 144 lbs

The correct answer is E

**Figure 5. Exam Problem Sp16-T1-11**

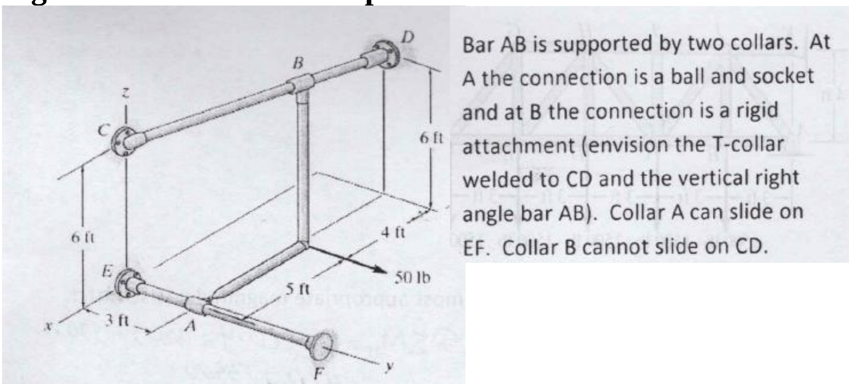



Q: What is the angle or direction of the resultant force as measured from the positive X-axis CCW?

A) 56º
B) 26º
C) 79º
D) 18º
E) 64º

The correct answer is A

**Figure 6. Exam Problem Sp16-T2-3**



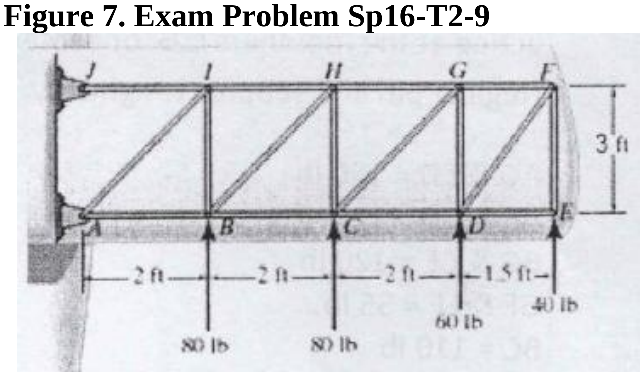

Q: If the indicated 50 lb load is applied, then what is reactionary force $B_y$?

A) -48 lbs
B) +52 lbs
C) +32 lbs
D) -112 lbs
E) -65 lbs

The correct answer is A

The highest observed correlation was between problem SP16-T2-9 (truss analysis problem) and the post-PSVT:R, figure 6. This result is inconsistent with the results from the exam and quiz data. This might be due to the reverse loading nature of the truss and the requirement to solve for the force in one of the angled members or shows the improved test taking skills of the students. The moderate correlation supports the relationship between students' spatial ability and solving truss problems and supports the inclusion of spatial training prior to the topic being introduced. A possible spatial training could include making a model of the truss in Figure 7, or a similar truss, than can be used to demonstrate who forces change based on varying loading conditions.

**Figure 7. Exam Problem Sp16-T2-9**




Q: Determine and select the force in member BH due to the loading experienced by the wing.

A) 325 lbs
B) 310 lbs
C) 140 lbs
D) 215 lbs
E) 205 lbs

The correct answer is D

**Limitations**

There are several possible limitations with this research. One possible limitation is the small sample size of exam specific problems. Since each exam had unique problems, each exam problem was only given to students in a single semester. Another limitation of this research is that students could rely on procedural knowledge rather than their spatial skills when answering exam questions. Furthermore, test-taking ability could have affected the results. Since data for exam problem data was acquired from spring semesters, seasonal factors could have effect performance. The ceiling effect of the PSVT:R could have skewed the data and altered the results.

## Conclusion

Spatial ability is moderately correlated with specific engineering statics topics: 2D and 3D reactions, bending moments, hydrostatic resultant forces, vectors, truss analysis, friction, and moment couples.  This research supports arguments for the inclusion of spatial training early in the semester, either in-situ if time permits or  prior to the topics of moment couples, solving reactions, friction, and truss analysis. Including spatial training prior to these topics could result in improved student performance in the class and improved student understanding on building block concepts essential to engineering. This work begins to granularly investigate specific areas of statics course content that correlate to spatial ability.

## Future Work

This research team plans to further investigate this topic by designing exam questions for the topics of 2D reactions, moment couples, friction, and truss analysis. Designing questions for these topics will allow for greater control in determining how each topic relates to different constructs of spatial ability. Another area this work could expand is determining how concepts in other engineering mechanics courses, such as mechanics of materials, relate to spatial ability. This research also aims to create short trainings that can be given prior to introducing spatially heavy topics.

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