The Relationship between Spatial Skills and Solving Problems in Engineering Mechanics

Abstract

In this Work-In-Progress study, a total of 47 students from upper division engineering courses offered at a Midwest public university completed a test of spatial skills and also were asked to solve five to six open-ended problems from introductory mechanics concepts. Results showed that a statistically significant positive correlation was found between spatial scores and the percent correct on the mechanics test. Using item analysis based on classical testing theory, individual problems were also examined to determine if spatial skills appeared to play a role in their solution. Some problems appeared to rely on spatial thinking; others did not. Results from this Work-In-Progress study will be used to conduct an in-depth study examining the relationship between spatial skills and solving problems in engineering mechanics. This paper outlines key findings from this Work-In-Progress study and makes recommendations for future work in this area.

Introduction

Spatial visualization is defined as "process of apprehending, encoding, and mentally manipulating three-dimensional spatial forms" [1]. Spatial cognition has been widely studied throughout psychology and education for more than 100 years [2-4]. Engineering students and engineering professionals exhibit some of the highest levels of spatial skills compared to their counterparts in other majors/careers [5-6].

Numerous studies have shown the link between spatial skills and success in engineering, and interventions aimed at enhancing spatial skills have demonstrated a concomitant improvement in student success, as measured by grades earned and retention/graduation [7].

However, a question still remains: how do well-developed spatial skills contribute to engineering student success? One hypothesis is that spatial skills contribute to a student's ability to solve unfamiliar problems. Recent studies have demonstrated that spatial skills contribute to success in solving problems from mathematics, chemical engineering, and electrical engineering [8-9]. For example, Duffy et al, [8] found a link between spatial skills and success in solving mathematics word problems among engineering students. In this study, students were first given a test of spatial cognition and then asked to factor an equation to solve for x such as:

$$x^2 - 9x + 14 = 0$$

All students, regardless of spatial skill level, were able to solve this problem when presented in this format. Then students were then given the following problem:

> You have a square lawn. You increase one side by 2 meters and the other side by 3 meters and you have doubled its area. What was the original size of the lawn?

When presented this way, the high visualizers could set up the equation ($2x^2=(x+3)*(x+2)$) and then solve for x. The low visualizers struggled to convert the words into an equation and thus were much less successful in solving this type of problem. The conclusion from this study was that spatial skills appear to play a role in the problem conception stage and not in the solution stage. The study outlined in this paper, extends this work to examine the impact of spatial skills on the ability to solve fundamental problems from engineering mechanics.

Method

Purpose of the Study

The first objective of the study was to determine the relationship between student spatial visualization skills and their ability to solve fundamental mechanical engineering problems. The secondary objective of the study was to identify the problems that show a strong connection to spatial reasoning. Once specific problems are identified, further studies will be performed to examine specific factors of the problem-solving methods used by engineering students and how they relate to spatial skill levels.

Participants

In fall 2019, students in their third or fourth year, who were enrolled in a Mechanical, or closely related, engineering program at the University of Cincinnati, were recruited for participation in this study through announcements in their upper division courses. A total of 47 students, including five female students (10.6%), participated in the study. Students were compensated $75 for their participation in the project. All research conducted through this project was monitored and approved by the Institutional Review Board at the university.

Procedure

The student participants completed the Mental Cutting Test (MCT, [10]), a test of spatial cognition, and then solved a series of five to six open-ended problems based on fundamental concepts learned in previous coursework, such as introductory statics and physics. The problems were administered in a neutral location outside of the student’s typical schedule, allowing for every student to be given the same amount of time to solve the series of problems. Students were given 30 minutes to solve the mechanics problems. Due to the time constraint, only students with competent knowledge would be able to solve every problem in the allotted time.

Measures

Mechanics Problems. The mechanics problems were created either by hand or through a statics textbook [11] that was comparable to the literature used in the students’ coursework. Some of the problems were focused on “day-to-day" work that is expected to be known by this point in their schooling; others were extensions of basic theory, where the students were asked to implement their knowledge in more complex applications of their prerequisite work. Based on previous work with engineering students solving word problems in mathematics, each of the problems on the Mechanics test were presented as word problems with no figures provided. Examples of two levels of difficulty used in the problems are provided in the following examples:

- A 5kg otter needs to cross a 10m wide stream that is flowing at 10m/s. Assuming the otter can swim at a rate of 2m/s, how far up stream must she start to end up directly across from where she is standing now? (Question 7)
- An airplane is flying at an altitude of 2500m and a constant speed of 900km/hr on a path that flies directly over an anti-aircraft gun. The gun fires a shot with a muzzle velocity of 500m/s and hits the airplane. Knowing that the firing angle is 60 degrees from horizontal for the gun, determine the velocity and acceleration of the shell at the time of impact (Question 8).

The student answers were rated on a binary system of being either incorrect or correct based on their response. Since the purpose of this pilot study was primarily to identify problems with a "spatial component," a binary grading scheme seemed appropriate. As we move on to our larger study using the problems we identified here, problems will be scored on a partial credit basis that accounts for problem conception and problem solution. We will be particularly interested in looking at how spatial skills relate to the problem conception phase (similar to the work done in mathematics word problem-solving). The eleven questions were administered in a random order through four variations of the test, where the students were either tasked with five or six problems (based on perceived difficulty by the researchers), depending on which test they had. Because a different number of questions was given to students in the four groups, scores are represented as a percent correct for the analysis portion of this paper.

Spatial Skills Test. The Mental Cutting Test (MCT), a measure of spatial visualization ability, was administered to the students. In this test, students are presented with an object on the left with an imaginary cutting plan passing through it. They are to imagine what the cross section would for the intersection of this object and plane. This test was selected primarily due to its general difficulty. Frequently, the spatial skills of engineering students are advanced and other potential tests of spatial cognition could exhibit a "ceiling effect," meaning that there would be less variability in the data. The test consists of 25 questions and each question presents five multiple choice options, with four distractors and one correct answer. The MCT is a timed test and students were given 20 minutes to complete it. Figure 1 presents an example item used from the test.

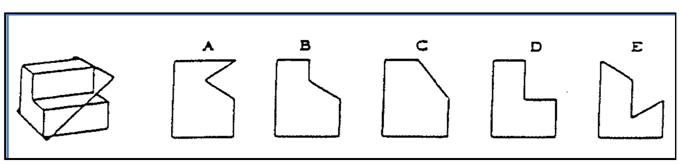

Figure 1. An example item on the Mental Cutting Test (Correct answer=D)

Data Analyses

Descriptive statistics of students' spatial and mechanics tests were first calculated. To satisfy the first project objective, we calculated a Pearson correlation coefficient between MCT and the mechanics test scores in percent correct. To satisfy the second project objective, we explored item characteristics of each mechanics question, such as Item Difficulty and Item Discrimination Indices, and their relationship with overall spatial ability.

Results

Relationship Between Students' Spatial Skills and Mechanics Problem Solving Skills

Table 1 shows descriptive statistics of student scores on the MCT and the Mechanics Test. There was no one who got a perfect score on either of the tests.

Table 1. Descriptive Statistics on Spatial and Mechanics Tests

Test	*M*	*SD*	*Min*	*Max*
Mental Cutting Test	15.21	3.94	6	23
Mechanics Test	44.89	19.97	0	80

Figure 2 displays the correlation between students' MCT scores, and the percentage of the number of problems correctly answered on the Mechanics test. As shown in the scatter plot, there was a positive and statistically significant correlation (*r* = 0.31, p=0.034) between the spatial skills test scores and the ability to solve the mechanics problems.

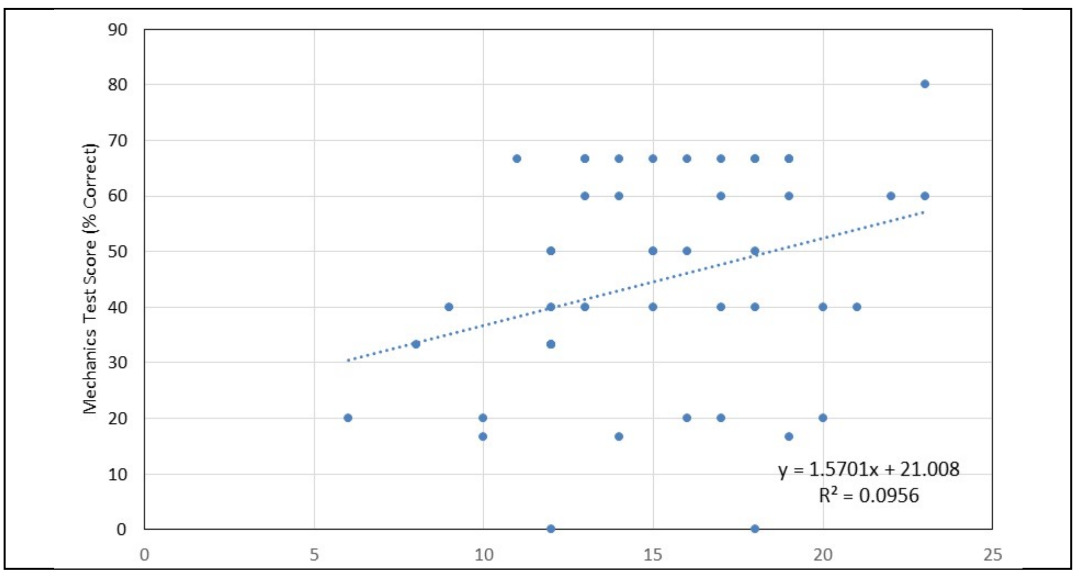

Figure 2. Correlation between mechanical engineering test and MCT scores

Charateristics of Mechanical Engineering Problems

After reviewing the overall scores, we looked into how students performed on the individual problems to see if there were specific questions that appeared to require better spatial reasoning than others. In this analysis, based on classical testing theory, we considered three different item (i.e., question) characteristics to explore the relationship of each individual mechanics problem with overall spatial ability. As shown in Table 2, the three item characteristics include Item Difficulty, Item Discrimination, and the Correlation with MCT score.

Table 2. Mechanics Problem Characteristics

Question	Description of Problem	Item Characteristics		
		Item Difficulty	***Item Discrimination***	***Correlation with MCT***
1	Dropped Ball/Angle and Velocity of Rebound	0.45	0.40	0.05
2	Graphing Displacement & Velocity of Dog Walking	0.88	0.41	0.30*
3	Maximum Speed of Race Car Going Around a Banked Curve	0.00	N/A	N/A
4	Location of Greatest Moment on a Fixed-Fixed Beam	0.25	0.30	0.05
5	Water Flowing into a Pool—Find Rate of Change in Height	0.45	0.58	0.13
6	Decelleration Due to Application of Brakes on a Scooter	0.84	0.72	0.24*
7	Otter in the River Problem	0.83	0.65	0.44*
8	Gun Ship and Airplane Problem	0.08	0.28	0.21*
9	Determine the Normal Force of a Block on an Incline	0.52	0.68	-0.01
10	Basic Statics—Sum of Forces Equals Zero	0.20	0.47	0.17
11	Greatest Force and Location of Greatest Moment on Cantilever Beam	0.48	0.46	0.28*

Note. $^{*}p < 0.05$; N/A = Not Applicable

The Item Difficulty relates to the percent of students who completed the problem correctly. The problems varied in required mechanics skills, leading to a broad spectrum in percent correct among the student participants. The Item Discrimination Index looked into the correlation between the question being answered correctly and an individual student's ability to succeed on the test as a whole; i.e., do the "good" students answer it correctly and the "weak" students answer it incorrectly. This index ranges from 0, where the results have no connection to a student's overall skill level, to 1, where the items are perfectly related. The focus for this part of the study was on the final category, the Correlation with the MCT scores. Like the Discrimination Index, the higher the value, the better related the two categories are. Interestingly, there was no one who solved question #3 on a race car in a circular motion on the banked curb correctly, implying that this was the most difficult question. Therefore, the Item Discrimination Index and the correlation coefficient with the MCT scores were not calculated for this item.

It can be noted that there were 5 questions (2, 6, 7, 8, 11) where spatial skills appear to be related to solving the problem with correlations greater than 0.2, which are statistically significant. While some problems like the otter in the river (Question 7) and the gun ship (Question 8) presented previously in this paper show strong connections to spatial skills, problems like the one provided below had very little to do with spatial abilities:

- A 10kg block is resting on a 27-degree incline. Determine the normal force acting on the block (Question 9).

Based on the analysis presented in Table 2, the following problems were selected for further analysis in our larger study:

- Otter in the River Problem (#7, presented previously)
- Gunship and Airplane Problem (#8, presented previously)
- A bird lands on a cantilever beam 'a' meters from the fixed end. What is the greatest force acting on the beam? Where is the greatest moment? (#11)
- A 1000 kg truck is pulling up a cargo load from the bottom of a 50 meters cliff. To help reduce the risk of damage a pulley is installed at the edge of the cliff. With a coefficient of friction of 0.3. What amount of force is needed to lift the 500 kg load from the bottom of the canyon? (#10).

Note that although the correlation with spatial for problem number 10 was not statistically significant, it was approaching significance ($r=0.17$). This problem was selected in order to balance the overall difficulty of the test, i.e., the desire was to have at least two "challenging" problems for our future work. In the future, we will be scoring problems on a non-binary scale, so having more difficult problems will assist us in making differentiations between students more precisely.

Conclusion

There has been significant research supporting the importance of spatial skills in the engineering field overall, but there is insufficient work done examining the specific areas where spatial skills appear to play a role in engineering student success. Solving problems with spatial components is common in the work engineers do. Challenging questions that require an understanding of the numerical values along with how they react in a three-dimensional space allows for the strong visualizers to outperform those who do not have well-developed spatial thinking skills. The results from this study highlight the need to ensure that all students are prepared for engineering success by having well-developed spatial skills.

Next Steps

The results from this Work-In-Progress study will be used to inform a larger study that examines the link between spatial thinking and engineering problem-solving in mechanics in more depth and also through the inclusion of biometric data gathering. We will use non-intrusive methods to record data, such as eye movement, heart rate, and skin conductivity, to better understand how the engineering students are reacting to the problem-solving process in terms of stress, both perceived and measured. We will be particularly interested in the stress levels of weak visualizers as they solve typical engineering problems. Additionally, further research will be performed examining the quality of sketches drawn by students to determine the link between spatial skills and sketch quality. Since high-quality sketches are often a critical first step in solving engineering problems, this aspect of the research can inform future efforts in potential interventions aimed at improving the quality of sketches produced by students as they solve problems.

In sum, results from this Work-In-Progress study will be used to conduct an in-depth study examining the relationship between spatial skills and solving problems in engineering mechanics. This paper outlines key findings from this Work-In-Progress study and makes recommendations for future work in this area.

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