# The Relationship Between Spatial Skills and Sketch Quality in Solving Problems in Engineering Mechanics

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*Abstract*—***Spatial visualization is the ability to imagine what an object looks like from various viewpoints or after the object has been rotated in space by some amount. Numerous studies have shown the link between spatial skills and success in engineering. But how do well-developed spatial skills contribute to engineering student success? In studies with elementary students, children with good spatial skills were able to create schematic sketches—sketches that aided in the solution of the given problem. Poor visualizers drew pictorial sketches—those that did not help the student then solve the problem. A pilot study was conducted to determine the link between spatial skills and the ability to solve problems from engineering mechanics. In this study, a total of 47 students from upper division mechanical engineering courses completed a test of spatial skills and were also asked to solve 5-6 problems from introductory statics/physics. Results showed that a statistically significant positive correlation was found between spatial scores and the percent correct on the mechanics test. In this paper, we examine the quality of the sketches made by students while they were solving the problems and categorize them as either schematic or pictorial. Examination of the spatial skill levels of students who make schematic sketches will be compared to the spatial skill levels of those who make pictorial sketches.***

*Keywords—spatial cognition, problem-solving, graphics, sketching*

## I. Background

Three-dimensional spatial skills have been an area of research for at least 100 years. In the 1960s, Smith [1] examined a large number of careers and concluded that there were at least 84 careers (at the time) where well-developed spatial skills were important to success. In particular, Smith noted that virtually all STEM fields require well-developed spatial skills. Building from that work, Arnheim [2] noted that of all technical fields, engineering relied on spatial thinking more than almost any other career. Numerous studies have also shown the link between well-developed spatial skills and engineering success [3], [4]. In addition, good spatial thinking skills have also been linked to success in computer science [5] and physics [6].

Van Garderen [7] conducted a study with 6th grade students (approximate age=11). She administered several tests of spatial cognition and presented them with the following question:

- The diameter of a can of peaches is 10 units. How many cans will fit in a box 30 units by 40 units (one layer only)?

She evaluated the sketches produced by the students in the solution of the problem and characterized the sketches as either "schematic" or "pictorial." Schematic sketches were those that assisted with the solution of the problem; whereas, the pictorial sketches did not. Figure 1 shows an example of a pictorial sketch and Figure 2 shows an example of a schematic sketch. Notice that the pictorial sketch shows a can with the correct diameter noted. The schematic sketch also shows a picture of the can, but in addition a layout of the dimensions of the box is shown with the diameter of the can marked off in both directions.

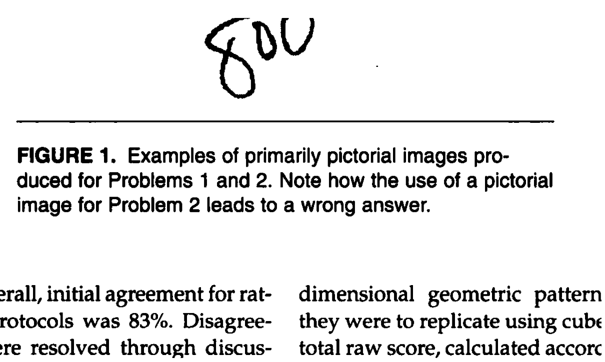
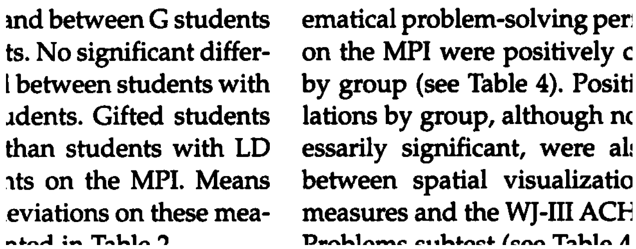



Fig. 1. Pictorial Sketch (van Garderen [7])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measures and the WJ-III ACH

Fig. 2. Schematic Sketch (van Garderen [7])

What she found, on average, was that students with high levels of spatial skills were more likely to produce schematic sketches. Conversely, students with low levels of spatial skills tended to produce pictorial sketches. Hegarty and Kozhevnikov [8] obtained similar findings in a study with 6th grade students solving mathematics problems.

## II. Sketching in Engineering Education

Sketching is often regarded as a core activity in engineering, especially in the early stages of the design process (ideation) [9], [10], [11]. Engineers often communicate with one another through sketches or through hand-sketched graphs. When two or more engineers are discussing an issue or a design problem, it is not usually very long before one person pulls out a piece of paper and a pencil to sketch their ideas in graphical form.

In the 1980s, McKim [12] pointed out that the need to think visually was understandably essential for artists. He also postulated that the ability to think creatively was related to our ability to sketch and proposed a model (Figure 3) of visual thinking.

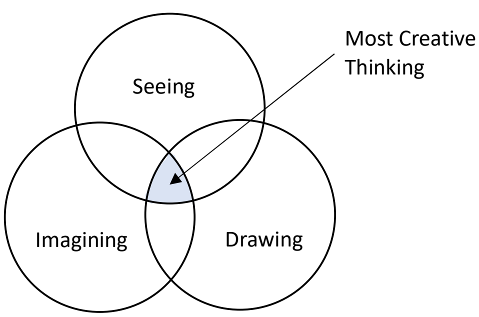


Fig. 3. McKim Model of Visual Thinking

To McKim, we are at our most creative when we are visualizing and sketching in a fluid state. The act of sketching frees our mind to think creatively and innovatively.

## III. Methodology

### A. Participants

In the fall of 2019, a total of forty-seven student participants completed the Mental Cutting Test (MCT; [13]), a test of spatial cognition, and then solved a series of 5 to 6 open-ended problems based on fundamental concepts learned in previous coursework, such as introductory statics and physics. Participants were recruited through brief presentation made in upper division courses in Mechanical Engineering at University X. 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. Due to the 30-minute time constraint, only students with competent knowledge would be able to solve every problem in the allotted time. The research was conducted under the supervision of the Institutional Review Board and participants were provided a small stipend for their efforts.

### B. Measures

*1) Mechanical Engineering Problems*

The mechanical engineering problems were created either by hand or through a statics textbook that was comparable to the literature used in the students' coursework. Some of the problems were focused on the "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. Examples of the two levels of difficulty are provided below:

- 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 shell 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. 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, depending on which test they had. Because a different number of questions given to students, scores were represented as a percent correct for the analysis portion of this paper.

*2) Spatial Skills Test*

The Mental Cutting Test (MCT), a measure of spatial visualization ability, was administered to the student. 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." The test consists of 25 questions and each question presents five multiple options with four distractors and one correct answer. For this test, students are asked to think about the object on the left being sliced by an imaginary cutting plane and determine what the resulting cross-section would look like. Figure 4 presents an example problem from the test.

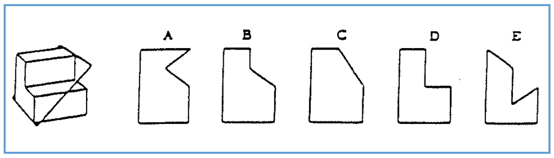


Fig. 4. An example item on the Mental Cutting Test (Correct answer=D)

## IV. Results

### A. Overall Scores

The total percent correct for each student was computed and compared to their score on the MCT. The average score on the MCT for these students was 15.21 or 60.8%. This compares to an average score of 11.22 (44.9%) obtained in a previous study [14] with upper division chemical engineering students at the same institution. The difference between mechanical and chemical engineering students was statistically significant ($p<0.0001$). A positive, statistically significant correlation ($r=0.39$) was obtained between MCT scores and the percent correct on the mechanical engineering problems. This magnitude of correlation is considered "large" signifying a strong relationship between spatial skills and the ability to solve physics/statics-type problems among mechanical engineering students.

### B. In-depth Analysis

One problem was selected for in-depth analysis of the quality of the sketches produced by the students and for other factors. For this analysis, the selected problem was:

- A bird lands on a cantilever beam *a* meters from the fixed end. What is/are the greatest force(s) acting on the beam and where is the greatest moment?

It should be noted that this problem actually has two parts to it. Students are supposed to identify the largest force acting on the beam and also identify the location of the largest moment acting on it. The sketches produced by the students were analysed. In this case, the "schematic" sketches were deemed to be those that showed a correct Free-Body Diagram (FBD) and the "pictorial" sketches that showed only a picture of the beam or showed a beam with an incomplete FBD. Figures 5 and 6 show pictorial sketches from this analysis and Figure 7 shows a schematic sketch. The MCT score of the student who produced the sketch is given with each. It should be noted that the "worst" sketch, i.e., the most pictorial, of those shown is the one in Figure 5 and that this student had the highest MCT score of the three shown. As with all analyses in educational research, correlations are not perfect measures and sometimes individual scores do not follow overall trends perfectly.

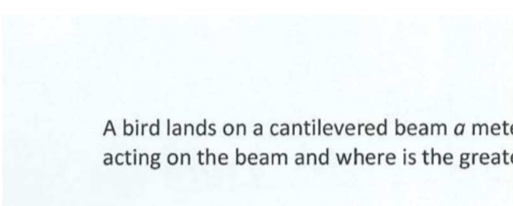


Fig. 5. Example Pictorial Sketch (MCT score = 14)

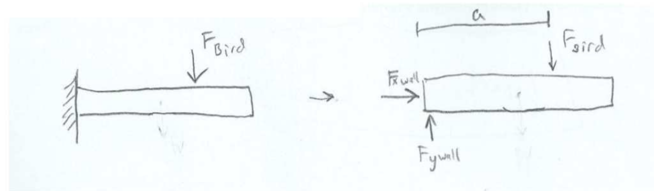


Fig. 6. Example Pictorial Sketch (MCT score = 12)

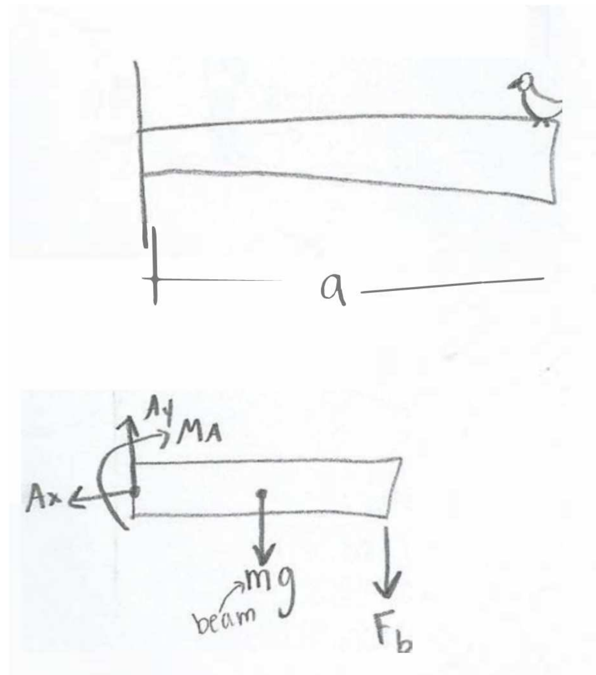


Fig. 7. Example Schematic Sketch (MCT score = 12)

In addition, the various components of the problem were examined individually. In this analysis, the spatial skills of the students who demonstrated proficiency on that aspect was compared to the spatial skills of those who did not demonstrate proficiency. The various aspects of the problem that were analysed were:

- **Force.** The students were asked to identify the greatest force on the beam. The correct answer to this was either a) the weight of the bird, or b) the weight of the bird plus the weight of the beam. It should be noted that the weight of the beam itself was not included in the problem description. Some students chose to include it in their analysis and others did not. Answers were noted as correct as long as they were consistent in their responses.
- **Moment.** Students needed to identify the *location* of greatest moment acting on the beam. The correct response to this was the reaction at the fixed support.
- **Either.** Students were marked correct if they identified either the correct force or the correct location of the moment. They were incorrect if they identified neither of these correctly.

- **Both.** Students were marked correct only if they identified both the force and the location of the moment correctly.
- **Free-Body Diagram.** If students sketched the correct FBD, identifying all forces/moments on the beam, they were marked correct. If they were missing any component of the FBD, they were marked incorrect. The student sketch shown in Figure 6 is missing the moment at the fixed end, so this was marked as incorrect.
- **Weight.** Although the students were not asked to consider the weight of the beam in their analysis, we examined whether or not they included this in their calculations.

Table 1 includes the data from this analysis. In this table, the values in the cell for Incorrect/Correct are the average MCT score, standard deviation, and sample size for the students who answered each factor either incorrectly or correctly.

TABLE I. DETAILED ANALYSIS OF STUDENT SOLUTIONS

| Factor | Incorrect | Correct | Significance |
|---|---|---|---|
| Force | 14.89<br>s=4.65<br>n=9 | 16.36<br>s=3.61<br>n=14 | p=0.404 |
| Moment | 12.50<br>s=3.89<br>n=6 | 16.94<br>s=3.45<br>n=17 | p=0.0158 |
| Either | 12.25<br>s=4.92<br>n=4 | 17.00<br>s=3.50<br>n=19 | p=0.0311 |
| Both | 14.55<br>s=4.25<br>n=11 | 16.92<br>s=3.58<br>n=12 | p=0.160 |
| FBD | 14.36<br>s=3.61<br>n=11 | 17.08<br>s=4.06<br>n=12 | p=0.105 |
| Weight | 14.93<br>s=3.97<br>n=15 | 17.38<br>s=3.81<br>n=8 | p=0.168 |

From the data presented in Table 1, it appears that spatial skills play a critical role in the solution of this problem, but especially in the identification of the location of the Moment acting at the fixed end of the beam. Statistically significant differences were found between the spatial skills of the students who answered this correctly compared to those who did not. This is apparent from the analysis both for "Moment" or "Either." There were only four students in all who got neither part of this two-part question correct and their spatial skills were significantly lower than those who answered at least one part correctly.

The difference in spatial skill levels for those who drew the correct FBD were higher than for those who did not. The difference was not statistically significant; however, the sample size for this analysis lacked power. A follow-on study that will include a significantly larger sample size is planned for the future to determine definitively if spatial skills contribute to the creation of correct FBDs in statics.

## V. CONCLUSIONS

As engineering educators, we often encourage our students to create sketches as the "first step" in solving a problem. And in fact, psychologists who have examined problem-solving in general, have found that being able to create schematic sketches reduces cognitive load so that we are better able to focus on solving the problem at hand. However, from the research conducted here, and elsewhere, it appears that students with weak spatial skills may have difficulty in creating schematic sketches as a first step in efficient problem-solving. This, in turn, likely impacts their ability to *correctly* solve engineering problems. One solution might be to help students develop their spatial skills so that they are better able to create schematic sketches in their mechanics courses and elsewhere in their engineering studies. Another approach might be to provide targeted instruction in how to created schematic sketches within specific mechanics courses, to ensure that students understand how to make these rudimentary sketches that will ultimately enable them to become better problem solvers. It is likely that most engineering faculty, who have excellent spatial skills, assume that creating these sketches are a simple feat and spend little time on explicit instruction in their creation. Students, especially those with weak spatial skills, would likely benefit greatly through deliberate instruction in how to create these schematic sketches that form the basis of good problem solving in engineering.


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