Spatial-Visual Skills and Engineering Design

by

Tiffany Tseng

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Abstract

The purpose of this study was to determine whether students with strong spatial-visual skills tend to design more complex mechanisms for the undergraduate course Design and Manufacturing I. The Purdue Spatial Visualization Test was administered to 137 students enrolled in the course. Test scores were compared to student self-evaluations of experience with tasks associated with spatial reasoning such as building origami models and sketching. The complexity of 34 student robots was analyzed using metrics such as the percentage of moving components in the mechanism. Gender differences in scores on the spatial visualization test were significant, consistent with results of prior studies. A significant correlation between spatial reasoning and origami experience was found for male students tested. Most mechanism complexity criteria were not found to be significantly correlated with spatial-visual ability, although the correlation between the percentage of moving components and spatial test scores approached significance with a negative correlation. These results suggest that strong spatial-visual abilities may be used to simplify engineering design rather than increase its complexity.

Thesis Supervisor: Maria C. Yang
Title: Assistant Professor of Mechanical Engineering & Engineering Systems

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Chapter 1

Introduction

Spatial-visual reasoning is a person's ability to mentally transform or manipulate an object in one-dimensional or multi-dimensional space. Spatial-visual skills are often utilized by engineers in tasks such as CAD design and part design and assembly. However, instruction on improving visualization skills is not always provided for engineering students. It has been found that spatial reasoning can be improved when such courses are provided [1, 10, 18], but comparatively little research has been performed to determine the importance of spatial-visual skills to engineering design, especially compared to other skills such as machining ability and competency using CAD modeling software. The purpose of this study was to determine whether a significant correlation exists between strong spatial-visual skills and complex mechanism design in the MIT mechanical engineering undergraduate course Design and Manufacturing I—Do students with high spatial-visual ability tend to design mechanisms composed of a large number of components integrated to carry out a complex motion or task?

Design and Manufacturing I, or 2.007, is a course that requires students to design and build a robot from stock materials in the course of one semester. The Purdue Spatial Visual Test: Visualizations of Views (PSVT:V) was administered to 137 students enrolled in 2.007 in the spring of 2009, and students' test scores were compared to the complexity of the mechanisms each student designed for the course. Although not always valued over simplicity, complexity was hypothesized to be a characteristic of designs produced by students with high spatial-visual abilities. This is because spatial ability is associated with understanding how physical objects can be assembled and how they can move with respect to other subcomponents; students with higher spatial skills may be better able to understand such integrated systems and may therefore be more likely to design them.

Complexity was measured with several objective and subjective metrics such as the total number of parts comprising the mechanism, whether the mechanism was constrained to planar or three-dimensional motion, and the originality of the mechanism compared to others in the class. Students were asked to rate their experience in skills associated with spatial-visualization ability such as sketching, building physical prototypes, making origami models, and using CAD software. These rankings were also compared to the PSVT:V test scores. Although it was not the main focus of the study, gender differences in scores were analyzed and compared to results from prior work. Prior studies have found that males tend to perform significantly better than females on spatial-visual tasks, so the results of this study were used to determine whether MIT students follow this trend.

By determining whether there is a correlation between students who score well on a spatial-visual examination and students who design the more complex mechanisms in the course, the role of spatial-visual skills in engineering design will be explored. It is expected that students with a higher spatial ability are better able to design robots that are more complex than that of their peers and may have a predisposition for more intricate engineering design. Research into this area of work can help determine whether it makes sense for universities to provide students with instruction on improving spatial reasoning abilities and help educators better understand the role of spatial-visual skills in design.

Chapter 2

Background

2.1 Spatial-Visual Ability

2.1.1 Definition

Spatial-visual skills are a measure of a person's dexterity in performing mental transformations of single or multi-dimensional objects. In 1985, Howard Gardner published his theory of multiple intelligences in *Frames of Mind* which identified Visual-Spatial intelligence as one of Gardner's six original intelligences [5]. Individuals with high visual-spatial intelligence are characterized by strong navigation skills and mental-recall abilities. Spatial-visual ability is believed to be an important skill for engineers and is utilized when performing tasks such as designing mechanisms and assemblies or creating digital models of parts using design software [10].

Visual-spatial reasoning is composed of several distinct skills including recognizing and perceiving the visual world, mental recall with or without the presence of physical stimuli, and transformations of objects in the physical domain [5]. Psychologists have categorized spatial abilities into two main types: spatial relations and spatial visualization [2, 18]. *Spatial visualization* concerns mental transformations and recall of separate subcomponents that make up an entire system while *spatial relations* involve transformations of a whole body. One could imagine that spatial visualization, the more complex of the two spatial functions, would be useful to mechanical engineerings designing mechanisms made of an assembly of parts that may be moving relative to one another.

Visual-spatial abilities are attributed to the left hemisphere of the brain where visual-spatial processing occurs. These skills evolve from an understanding of space that emerges during infancy, typically categorized under Piaget's Sensory-Motor stage of cognitive development [20]. Children at this stage, who are usually under the age of two, develop navigation skills and learn to appreciate and predict the trajectory of moving objects. Once the child develops into the Preoperational stage, usually from the ages of 2 to 7, the child is able to actively manipulate objects, characterized by *operative knowledge* rather than *figurative knowledge*. *Figurative knowledge* is one's ability to remember how an object appears while *operative knowledge* allows an individual to imagine an object from a different perspective by mentally rotating or transforming the object [5].

Operative knowledge can be fostered through the use of games or physical manipulatives such as blocks and can be enriched through art and geometry courses [11, 17]. However, researchers have found that most geometry classes are linguistic based and, as a result, do not improve visualization skills [11]. The mechanical engineering department at MIT currently does not offer any courses dedicated to engineering drawing or graphics, although some classes dedicate one or two lectures to drafting in their syllabi.

In a study performed at the University of California at Berkeley, ten practicing engineers were interviewed to determine how they utilized their spatial-visual skills during everyday work tasks [10]. It was found that spatial reasoning contributed to design but was rarely used in isolation; for example, spatial reasoning could be coupled with descriptive geometry when drawing a component. Similarly, with this study, students combine spatial-visual abilities with machining, sketching, and CAD skills to create their robots.

Spatial visualization is commonly assessed with tests that involve multidimensional transformations. For this study, the Purdue Spatial Visualization Test: Visualizations of Views was used to test engineering students' spatial ability.

2.1.2 Purdue Spatial Visualization Test: Visualization of Views

The Purdue Spatial Visualization Test is a standardized test composed of three subtests: Visualizations of Rotations Test (PSVT:R), Visualization of Views Test (PSVT:V), and Visualization of Developments Test (PSVT:D). For this study, the Visualization of Views test was used so that the results could be compared to prior research performed at MIT in the Man-Vehicle Laboratory [15]. The test involves *perspective-taking* which requires test-takers to imagine how an object would appear if it were seen from a perspective other than their own.

The PSVT:V test consisted of 30 multiple choice questions requiring students to imagine how a three-dimensional object would appear from a given perspective. An example problem is shown in Figure 2-1.

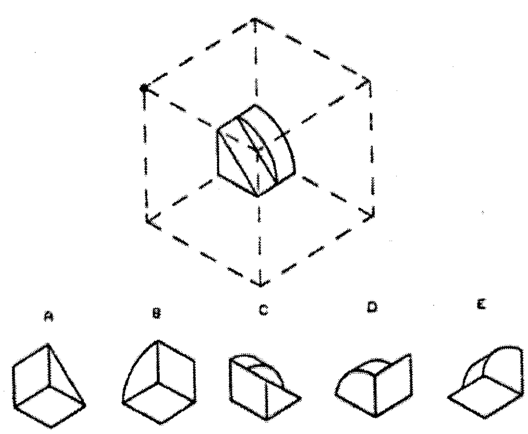


Figure 2-1: PSVT:V test question [7]

The center of the cube contains a three-dimensional figure. Each answer choice represents the same figure seen from a different viewing position. The student should imagine what the figure would look like if viewed from the marked viewing position indicated by the dot on the edge of the cube. In this example, the dot is located on the left edge of the cube.

2.1.3 Gender Differences

There is a large amount of literature dedicated to gender differences noted on spatial-visualization tasks. It has been found that males, on average, significantly outperform females on spatial visualization tests [13, 14, 16]. These differences have been attributed to several factors including biological, social and cultural, and educational factors and are believed to contribute to the fact that males tend to outnumber females in science and mathematics fields.

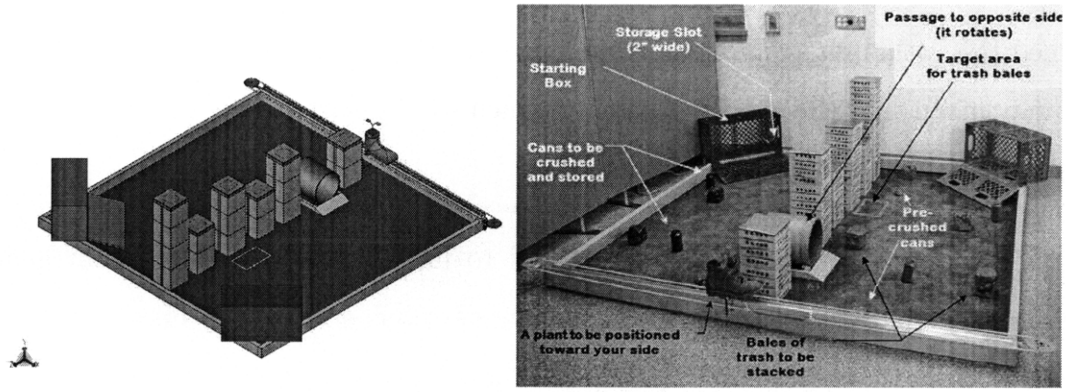
Biological differences that may affect spatial reasoning are brain lateralization [12], the x-chromosome [9], and puberty timing [22]. Brain lateralization studies have found that males have a greater degree of lateralization, meaning that the left side of the brain that is responsible for visual-spatial operations is dominant [12]. Others believe that spatial ability may be a recessive trait carried on the x-chromosome [9]. Sex differences may also be a result of the timing of puberty; Researcher D.P. Waber found that adolescents who had matured earlier, regardless of sex, had lower spatial ability than adolescents who matured later [22]. Since females tend to mature earlier than males, there may be a biological change that occurs during maturation that affects visual-spatial skills and therefore leads to a decrease in ability. Research has even found that women tend to score significantly higher ($p < 0.0001$) on spatial-visual tests during their menstrual period when their estrogen levels are lowest compared to their mid luteal period when estrogen levels are higher [19].

Further studies have shown that testing conditions may contribute to differences in scores. In a study performed by Professor Jill M. Goldstein [6], no significant difference between male and female scores on spatial reasoning tests appeared on untimed test although a significant difference was apparent when the test was timed. This may mean that the conditions under which we measure spatial intelligence could contribute to gender differences.

Although numerous studies have attempted to find a reason for significant gender differences on spatial-visual tasks, no single answer has emerged to answer this question. It is likely that a combination of all of these factors causes differences in skill [8]. However, studies have shown that women were able to increase their spatial ability after instruction so that even if there are apparent differences in ability at the onset, these differences can be minimized with training [1, 10, 18].

2.2 2.007: Design and Manufacturing I

The students tested in this study were enrolled in the MIT mechanical engineering class Design and Manufacturing I, or 2.007. 2.007 is offered to undergraduate students at MIT majoring or minoring in mechanical engineering. The majority of the students in the course are second-year students who have taken introductory courses in mechanics and materials, dynamics and controls, or thermodynamics. In the class, students design and build their own individual robot out of stock materials over the course of one semester. At the end of the semester, students use their robots to compete on a contest table that is uniquely designed for their class. Each year, the design of the table changes; this year, the table has cans, bales, and a plant that students must manipulate to score points. A solid model of the competition table is show in Figure 2-2a, and a photograph of the table is shown in Figure 2-2b. The actual competition table measures 7.8 feet on each side.



(a) Side view of 2.007 table [3] (b) Photograph of completed 2.007 table [4]

Figure 2-2: 2.007 competition table

Students prioritize which functions they would like their robot to perform in order to score the most points during the competition. During the competition, two robots compete on the table at the same time in rounds that last sixty seconds each. Students may choose to build defensive robots that block their opponent rather than score points.

The class is structured such that students learn to design separate components of their robot before a final integration process. First, students determine what goals they would like their robot to accomplish on the table. They then design mechanisms on paper that can carry out their desired tasks. Finally, the mechanism is solid modeled, fabricated in the machine shop, and tested on the table. Mechanisms designed with a specific task are defined as *modules*, and every robot has a *Most Critical Module* (MCM) that performs the task the student believes is most important or is most likely to fail. Each student builds and tests his or her MCM first before building other modules so that the MCM can be fully tested. As more modules are added to the robot, each student must integrate all components into a robot that can be remote controlled for the competition.

2.007 is the first of several required courses for mechanical engineering majors that requires students to learn about the iterative design process and fabricate a physical product. Several visualization techniques are taught in the course, including basic drafting, solid modeling, and prototyping. For most students, 2.007 is their first experience working in a machine shop and building a complete mechanical system. As a result, the students in 2.007 were a valuable resource for testing whether visual-spatial skills possessed by students at the beginning of the course aid them in creating more advanced mechanisms.

2.3 Statistical Analysis

The Spearman ranking correlation was used to determine whether a correlation exists between the PSVT:V test scores and the data collected on MCM complexity. Spearman's rank correlation coefficient, R_s is given by:

$$R_s = 1 - \frac{6\Sigma(d_i)^2}{n(n^2-1)} \tag{2.1}$$

where d_i is the difference between the ranks of the values being correlated, X_i and Y_i, and n is the sample size. R_s values are always between -1 and 1, where values between 0 and 1 indicate a positive correlation between the two data sets, and R_s values between -1 and 0 indicate a negative correlation. For example, in correlating PSVT:V scores and origami skill, X_i would be a matrix containing all PSVT:V scores and Y_i would be a matrix containing the corresponding origami skill scores. The significance of the obtained Spearman rank correlation coefficients was determined using a t-test, and results were considered significant at a probability of 0.05, meaning that the effect would occur at random less than 5 times out of 100.

The Wilcoxon rank-sum test was used to determine whether there was a statistically significant difference between average female and male scores. The smallest of the sum of ranks calculated for each data set is used to determine significance. The sum of ranks for the first set of data is calculated by:

$$T_1 = \frac{n_1(n_1 + 1)}{2} \tag{2.2}$$

where n_1 is the sample size of data set 1 (the females) and T_1 is the observed sum of ranks for data set 1. The sum of ranks for the second data set is calculated by:

$$T_2 = \frac{n_2(n_2 + 1)}{2} \tag{2.3}$$

where n_2 is the sample size of data set 2 (the males). Again, the differences were considered statistically significant at a probability of 0.05.

Chapter 3

Methodology

Students in 2.007 were given the Purdue Spatial Visualizations of Views Test at the beginning of the course. Halfway through the semester, the Most Critical Modules of the students' robots were assessed based on several criteria to measure complexity. The data collected for each MCM was then compared to the scores each student received on the spatial test.

3.1 Visualization of Views Testing

The Purdue Spatial Visualizations of Views Test (PSTV:V) was administered to 137 mechanical engineering undergraduate students (79 male, 58 female) during the second week of classes. Students took the test before a lecture on drafting, so only skill level prior to this lesson was tested. Students were given ten minutes to take the test, and the test scores were not factored into the students' overall grade for the course. The exam scores were calculated as the number of correct answers minus one quarter of the number of incorrect answers (of the questions answered) in order to minimize random guessing and to avoid heavily penalizing for not completing the test. This scoring algorithm was used in a prior study conducted by the MIT Man-Vehicle

Laboratory [15]. With this scoring, the maximum possible score on the test is 30.

3.2 Self-Evaluation Survey

A self-evaluation survey was attached to each test and was completed directly before the students started the PSVT:V test. The survey asked students to rank their experience with the following tasks: sketching, using CAD software, building physical prototypes, and making origami figures. A copy of this survey can be found in Fig A-1 in the Appendix. All of these tasks are associated with spatial-visual thinking. Students rated their experience in each of the categories on a 1-5 scale with 1 indicating no experience, 3 indicating average experience, and 5 indicating substantial experience. These rankings were compared to each student's PSVT:V test score to determine whether there was any correlation between a particular skill and spatial-visual ability.

3.3 Measuring MCM Complexity

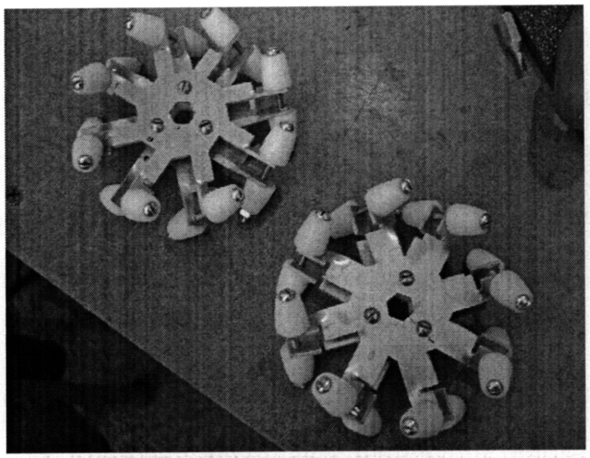
Halfway through the semester, students were required to have designed, built, and tested their robot's Most Critical Module (MCM). Thirty-four students (19 males and 15 females) were interviewed about their MCMs, and a combination of objective and subjective metrics were used to measure the complexity of their modules. Interviews were informal and held during lab sessions; each interview lasted approximately five minutes. Each MCM was photographed and analyzed in person in order to accurately count its number of components. Of the students interviewed, three of the students scored below one standard deviation below average on the PSVT:V test, 19 scored between one standard deviation below and one standard deviation above average, and 12 scored above one standard deviation above average. Female scores were compared to the average female score while male scores were compared to the average male score because of the significant gender difference found in average test scores.

The objective metrics used to measure complexity were the total number of components in the MCM, the percentage of custom-made components, the percentage of moving components, degrees of freedom, and planar vs. three-dimensional movement. These criteria were selected as measures of mechanism complexity that could in turn differentiate students who were strong spatial thinkers. It was hypothesized that students who needed to account for a large number of parts in their robot's design, especially moving parts, would have a higher spatial ability; this is because they need to think about how each part integrates with and moves against or with others. It was also hypothesized that students who build components that moved in multiple dimensions as opposed to being constrained to a single plane would have higher measured spatial ability. Mechanisms that were constrained to planar movement were given a score of 1 while three-dimensional movement was given a score of 2.

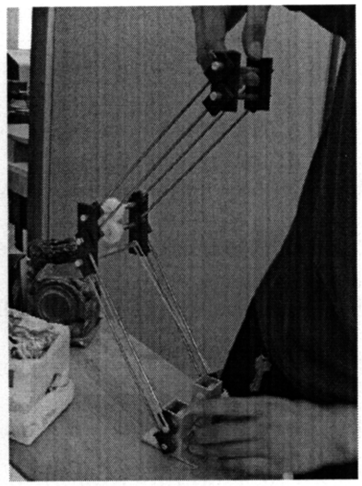
The total number of components in the mechanism was counted as all the separate components that made up the MCM excluding fasteners such as screws and rivets. Pre-made components such as gears and motors were counted in the total number of components. Motors and air cylinders were counted because several students used more than one in their MCM, leading to an MCM that had multiple degrees of freedom.

Custom-made components were counted as parts that the student machined from stock material. Air cylinders and motors were counted in the total number of components, but these parts were pre-made and were not included in the number of custom-made components. Custom-made components include parts that were bent, cut, or in any way modified from its original form.

The number of moving components was counted as the number of parts that rotated with respect to a stationary component or components of the MCM. Two examples are shown in Figure 3-1. For the omnidirectional wheels shown in Figure 3-1a, each delrin piece rotated with respect to the aluminum frame. As a result, the rotating delrin pieces were counted as moving components, leading to a total of 32 moving parts. For the crane shown in Figure 3-1b, all parts moved with respect to the stationary base held by the student in the photo. All parts excluding the ones on the base were counted as moving components, leading to a total of 38 moving parts.



(a) Omnidirectional wheels (32 moving parts)

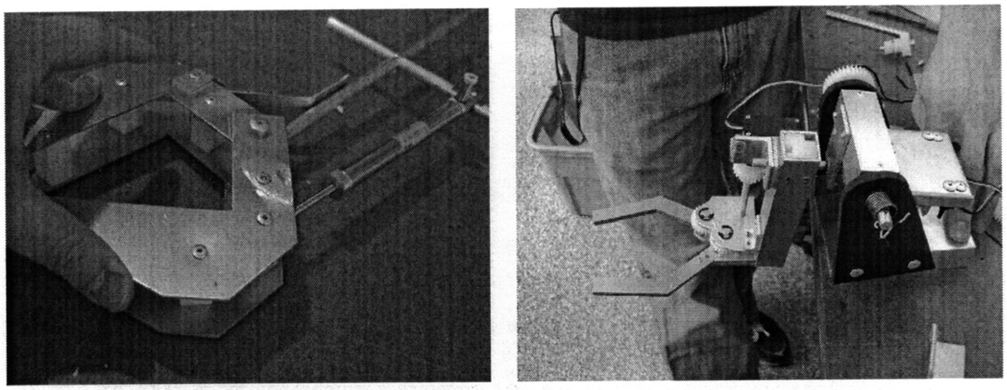


(b) Crane (38 moving parts)

Figure 3-1: Examples of MCMs with moving components

Two subjective criteria were used to judge the MCMs: originality and complexity. Both were judged on a scale from 1-5 with 5 being the highest score. Each MCM was judged by two people: Tiffany Tseng, the author, and Lawrence Neeley, a lab instructor for the class. The average of the two scores was used to compare to the PSVT:V scores.

Originality was defined as how novel the mechanism was compared to the other 34 mechanisms analyzed in the study. For example, many students created a claw that would be used to pick up crushed cans or bales from the table. Because most of the class had created a claw as their MCM, most claws were given an average score of 3 for originality unless there was a factor that made one more distinctive. Such an example is shown in Figure 3-2. Figure 3-2a is a claw mechanism that utilized an air cylinder to open and close; the mechanism had one degree of freedom and was given an originality score of 2.5. Figure 3-2b is a claw mechanism that was designed with three different gear trains, allowing the claw to open and close, rotate side-to-side,



(a) Claw mechanism 1 (b) Claw mechanism 2

Figure 3-2: Two claw mechanisms

and move up and down; this MCM was given a higher originality score of 3.5.

Complexity was defined as an overall impression of how intricate the mechanism was compared to the other 34 mechanisms in the study. This was a combinatory score that took into account the number of parts, degrees of freedom, and how well the mechanism was able to accomplish its intended goal. The omnidirectional wheels shown in Figure 3-1a were given a complexity rating of 5 because of the large number of components and moving parts in the module. An example of a module given a complexity rating of one is shown in Figure 3-3. The blocking mechanism shown in Figure 3-3 is a stationary bracket that is placed on the opponent's target area, preventing the opponent from scoring points. Because it contains no moving parts and was made of a relatively small number of components, this module was given a complexity rating of 1.

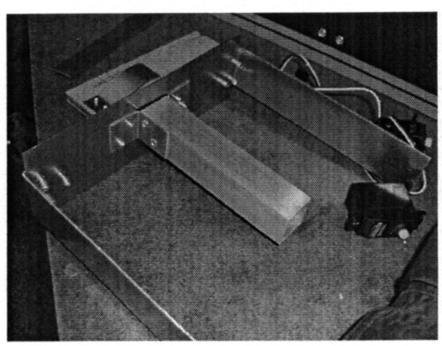


Figure 3-3: Example of module with complexity rating of 1

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Chapter 4

Results

Scores on the PSVT:V test were analyzed with data collected on students' robot modules. First, the PSVT:V scores were examined to find whether gender differences prevalent in prior work were present among MIT students. Next, the PSVT:V scores were compared to the results of the self-evaluation surveys. Finally, PSVT:V scores were correlated with the MCM complexity measurements.

4.1 PSVT:V Test Results

On average, students completed 24 questions (STD: 6.3) with scores ranging from 0.75 to 30. The three students that answered less than ten questions were not counted since this was lower than two standard deviations below the mean. Excluding the three students, there were 134 total students tested (78 males and 56 females). A histogram of the number of completed answers is shown in Figure 4-1.

Significant gender differences in test scores were found as shown in Table 4.1. Using the Wilcoxon rank-sum test, the difference between female and male scores was found to be highly significant (p: 0.00095).

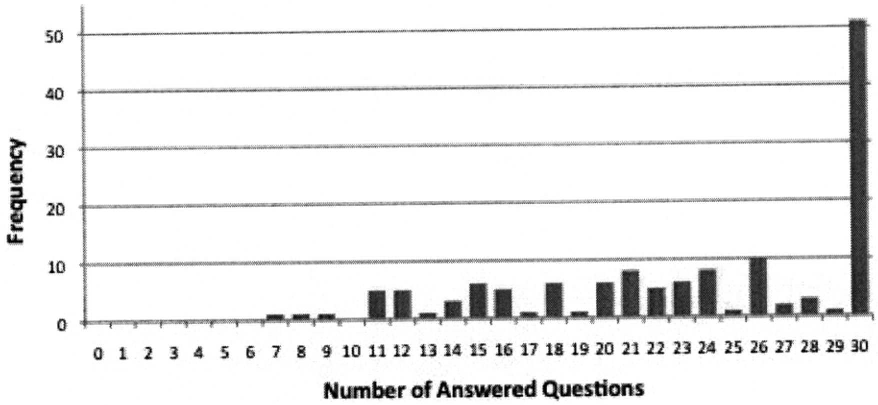


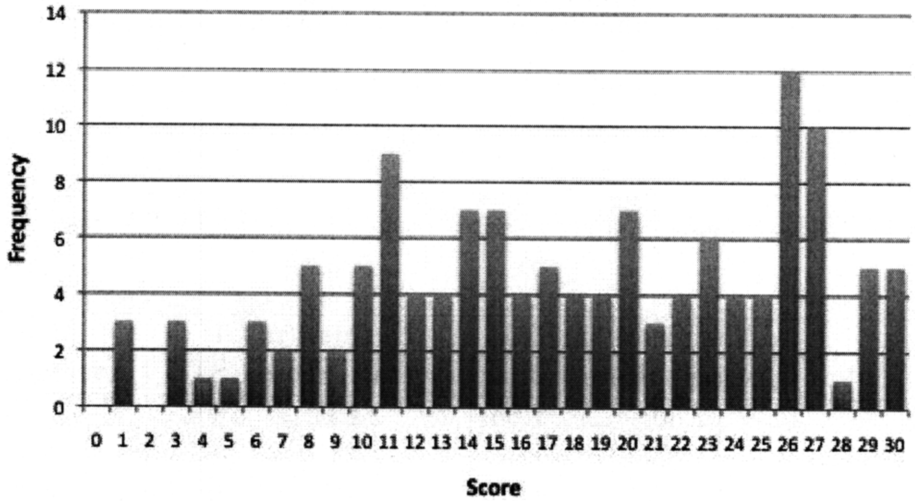
Figure 4-1: Histogram of number of answered questions (n: 134)

Table 4.1: Number of questions answered and PSVT:V scores by gender

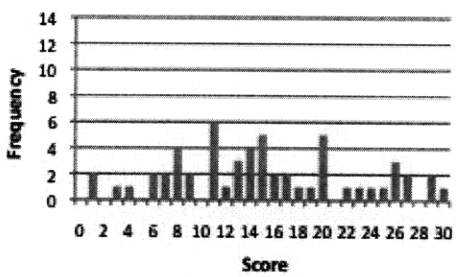
Sample	Questions answered	STD	Score	STD
Entire class (n: 134)	24	6.3	17.9	8.0
Female students (n: 56)	23	6.5	15.3	7.4
Male students (n: 78)	25	6.0	19.9	7.5

Histograms of scores for the entire class and for female students and male students are shown in Figure 4-2.

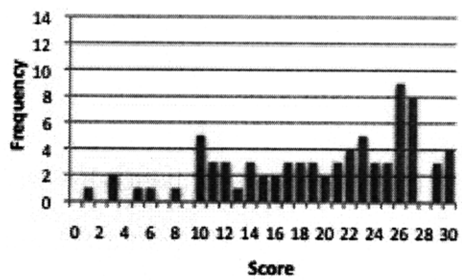
Using the Wilcoxon rank-sum test, the difference in the total number of questions answered was not found to be significant (p: 0.055), with females answering 23 questions on average (STD: 6.5) and males answering 25 questions on average (STD: 6.0). However, the difference between the percentage of right answers of the questions answered by males and females was statistically significant (p: 0.0019), meaning that although both genders completed a similar number of questions, females answered a greater percent of questions incorrectly.



(a) Scores for entire class (n: 134)



(b) Scores for female students (n: 56)



(c) Scores for male students (n: 78)

Figure 4-2: Histogram of scores by gender

4.2 Survey Results and PSVT:V Test Scores

The students' self-evaluations of their experience in sketching, using CAD software, building physical prototypes, and making origami figures were correlated with their PSVT:V test scores. On a paper-based survey, students were asked to rate their experience in these skill sets on a scale of 1-5 with 1 indicating no experience, 3 indicating basic experience, and 5 indicating substantial experience. There were two female students and one male student that did not complete the survey of the 137 students tested, so their results were not used for this analysis.

Table 4.2 shows the average scores students gave themselves for each skill set. As can be seen from the table, males and females varied the most in their evaluation of their prototyping experience and origami skills. No average scores were above a 3, the score equivalent to a rating of "basic experience."

Table 4.2: Self-evaluation survey scores by gender and PSVT:V test scores

	All students (n: 131)		Females (n: 54)		Males (n: 77)	
Skill Set	Average Score	STD	Average Score	STD	Average Score	STD
Sketching	2.80	1.06	2.83	1.15	2.78	1.01
CAD experience	2.32	1.20	2.31	1.24	2.32	1.19
Prototyping	2.82	1.16	2.69	0.98	2.92	1.26
Origami skills	2.98	1.26	2.61	1.25	2.08	1.22
PSVT:V score	18.00	7.54	15.13	7.54	19.9	7.38

Table 4.3 shows the Spearman correlation values found between each skill set ranking and the PSVT:V scores. Analyzing the entire class yielded no statistically significant correlations (no α values less than 0.05). However, when analyzing these correlations based on gender, one statistically significant correlation was found between origami skill and the PSVT:V scores for males. For this correlation, R_s: 0.2476, leading to a significance level of 0.01 (for a significance level of α: 0.01 (two tailed), R_s must be greater than 0.233 [21]).

Table 4.3: Correlation of self-evaluation survey scores and PSVT:V test scores

	All students (n: 131)		Females (n: 54)		Males (n: 77)	
Skill Set	α	R_s	α	R_s	α	R_s
Sketching	0.938	-0.007	0.246	0.161	0.178	-0.155
CAD experience	0.696	-0.035	0.300	-0.144	0.903	0.014
Prototyping	0.797	-0.023	0.757	0.043	0.233	-0.137
Origami skills	0.399	0.074	0.759	-0.043	**0.030**	**0.248**

4.3 MCM Complexity and PSVT:V Test Scores

MCM complexity data was collected for 34 of the students' robots in the course and is shown in Table 4.4. Students were asked to estimate what percent complete their MCM was at the time of their interview. On average, the MCMs were 84% done.

Table 4.4: MCM complexity data for all students (n: 34, 19 males, 15 females)

Complexity metric	Range	Average	STD
Number of components	3-64	21.6	15.2
Percentage of custom-made components	7.8-100%	67.4%	32.0%
Percentage of moving components	0-100%	55.6%	28.6%
Degrees of freedom	1-3	1.4	0.5
Planar/3D motion	1-2	1.4	0.5
Originality score	1-4.5	3.2	0.9
Complexity score	1-5	3.1	1.0

The students were divided into three different groups: the lower tier, or students who scored more than a standard deviation below the average PSVT:V score, the middle tier, or students who scored between one standard deviation below and one standard deviation above the average PSVT:V score, and the upper tier, or students who scored above one standard deviation above the average PSVT:V score. Because a significant gender difference was found in PSVT:V scores, females were compared to the average female PSVT:V score, and males were compared to the average male PSVT:V score. Figure 4-3 displays the differences noted among the three tiers.

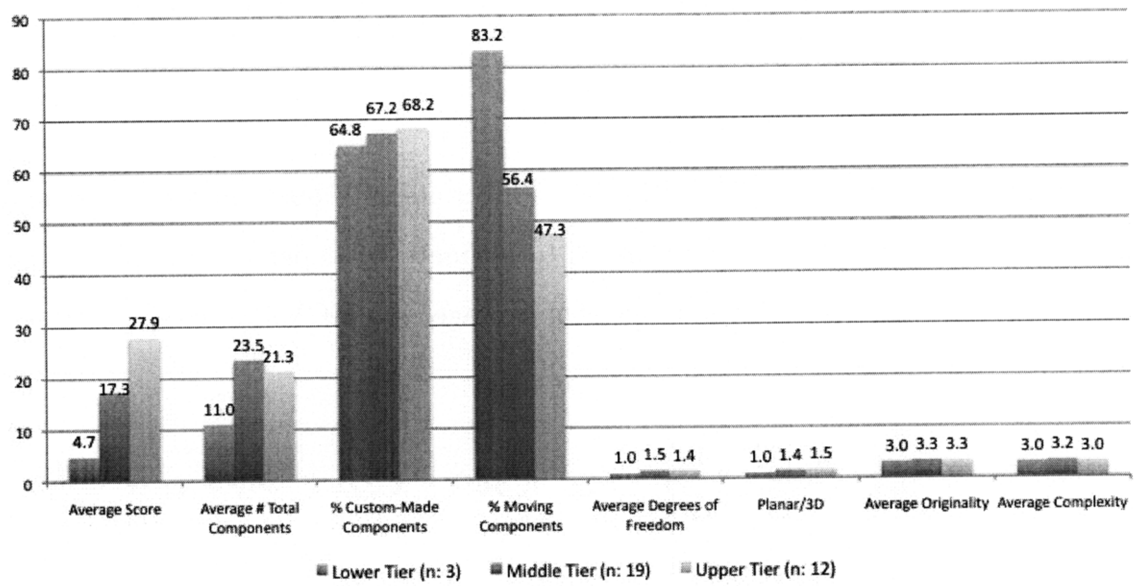


Figure 4-3: MCM complexity criteria and scores for three tiers of students (n: 34)

The criteria used to measure the complexity of the student's MCMs were not found to be significantly correlated with PSVT:V scores as shown in Table 4.5. However, the correlation between the percentage of moving components and PSVT:V scores approached significance with α: 0.059. Surprisingly, the correlation was found to be negative (R_s: -0.328).

Table 4.5: Correlation of MCM complexity and PSVT:V test scores for all students (n: 134)

MCM analysis criteria	α	R_s
Total number of components	0.413	0.145
Percentage of custom-made components	0.877	-0.028
Percentage of moving components	**0.059**	**-0.328**
Degrees of freedom	0.771	0.052
Originality	0.453	-0.133
Complexity	0.626	-0.087
Planar vs. 3D motion	0.479	0.126

Chapter 5

Discussion

5.1 PSVT:V Scores

For this study, the average score on the PSVT:V test was 19.9 (STD: 8.0). Test scores of the 2.007 students were slightly higher than those found in a study conducted by the MIT Man-Vehicle Laboratory [15]. In the Man-Vehicle Laboratory study, 7 individuals were tested (3 female and 4 male), and the average score was a 17.29 (STD: 6.82) with no noted gender differences. Significant gender differences were found between female and male test scores in the 2.007 study, which is similar to results obtained in prior work (see section 2.1.3). On average, females received a score of 15.3 (STD: 7.4) while males received a score of 19.9 (STD: 7.5).

5.2 Survey Results vs. PSVT:V Scores

Students' self-assesments of experience level in sketching, using CAD software, prototyping, and making origami figures was correlated with PSVT:V scores using the Spearman rank correlation (see Table 4.2 and Table 4.3). A statistically significant correlation between origami skill and PSVT:V scores was found for male students (p: 0.030, R_s: 0.248). Analyzing test scores of the entire class without separating by gender yielded no other statistically significant correlations between experience level in the aforementioned skill sets and PSVT:V scores.

This result may be caused by limitations associated with self-assessments. All students vary in their ability to asses their own experience level. Ideally, each skill set would be tested in order to better evaluate each student's skill level, but this was not possible within the scope of the project. There is also a distinction between experience and skill level which the survey did not take into account; a person with substantial experience may not necessarily be highly skilled and vice-versa. The survey only asked students to rate how experienced they were, not how skillful they believe they are. Skill level, however, is also difficult for people to assess without having a baseline for comparison.

Furthermore, the skill sets on the survey may rely more heavily on skills other than spatial-visual ability. For example, sketching may more heavily rely on motor coordination, and prototyping may be more dependent on machining ability. Since engineers draw on many different types of skills to perform these tasks, spatial-visual ability alone may not necessarily play a significant role.

Although no statistically significant correlation was found between female origami experience and PSVT:V score, a significant correlation was found between male origami experience and PSVT:V score. Males on average rated their experience level in creating origami models at 2.08 (STD: 1.22) while females rated their experience at 2.61 (see Table 4.3). Males on average scored themselves about 0.50 points lower on origami experience than did females, so it may be possible that although females on average had more experience, the few males that rated themselves highly are more skilled. However, it is not possible to know this without testing students individually on their skill level.

5.3 MCM Complexity vs. PSVT:V Scores

MCM complexity was correlated with PSVT:V scores as shown in Table 4.5. It was found that the correlation between the percentage of moving components in an MCM and PSVT:V scores approached significance with a negative correlation (α: 0.059, R_s: -0.328). This suggests that students with high spatial intelligence tend to simplify design rather than increase its complexity. The hypothesis that students with better spatial reasoning skills would create MCMs with more moving components, therefore, was not found to be true. In a study conducted by Maria C. Yang, fewer number of parts in a device correlated with better grade and contest ranking for students in a mechanical engineering course at the California Institute of Technology [23]. This idea is supported by the finding that the percentage of moving components was negatively correlated with PSVT:V score. It may be possible that students with higher spatial ability are better able to simplify designs mentally so that their mechanisms they eventually build require less parts.

No other metrics used to measure MCM complexity were found to be significantly correlated with PSVT:V scores. This lack of correlation can be the result of several factors. First, students may not necessarily choose to design a complicated mechanism to complete a task; in fact, many students will be more inclined to design a simple mechanism that is reliable and that they believe they can complete within a reasonable timeframe. Students who complete their robots earlier in the semester and are able to devote more time to practice driving and controlling their robot before the competition tend to do well in the competition despite having simpler modules. Students that prioritize building more robust and reliable mechanisms over ones that are more complex or novel often do so strategically.

Furthermore, students sometimes choose to design robots that act defensively and block their opponent rather than score points, and these robots often do well in competition. Even a robot with more complicated modules that can be consistently deployed on the table may not be able to do so with intererence from an opponent.

For example, one mechanism designed by a student who scored a perfect score on the PSVT:V test had no moving components and was simply used to block an opponent's scoring area as shown in Figure 5-1. Because the competition relies heavily on strategy, students that have high spatial-visual intelligence may not necessarily exert their efforts on designing complex mechanisms.

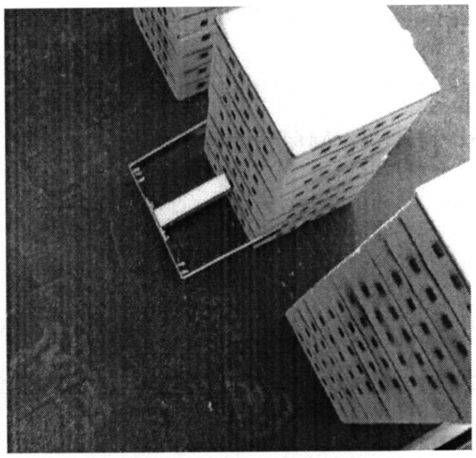


Figure 5-1: Blocking component

One solution may be to test students who intentionally design mechanisms to score points on the table rather than play defensively. However, this still does not take into account the students who intentionally design a simpler mechanism that is reliable. One way to more closely study this is to considered how each student ranks in the seeding rounds preceding the competition. During seeding, students are able to score as many points as they can during the sixty-second time frame. Students do not compete against another robot during the seeding rounds, so they are able to control their robots without the possibility of interference from an opponent. The scores from these seeding rounds could potentially reveal whether or not students with strong spatial-visual abilities build robots that are capable of scoring more points. Students' placement in the competition could also be correlated with PSVT:V scores, but the data may be flawed due to randomness associated with the opponent a student is paired with.

Another problem with judging mechanisms is that students are able to observe others' work which causes many designs to be repeated. It is likely that one or several students decided to design a claw and most of the class followed. Also, although students are expected to work independently on their robot, there is no penalty for students who choose to work together and design the same mechanism for each of their robots. This was the case for one group interviewed where one student scored below one standard deviation below average and the other student scored one standard deviation above average; both worked together to create the same mechanism for the competition. Perhaps in a future study, these situations can be discounted from the study since each individual's contribution to the project is difficult to determine.

A final reason that spatial visual skills may not correlate with MCM complexity is that it does not take into account the motivation of the student. A student with high spatial abilities may not be academically motivated to exert effort into the class. One correlation that could be performed is a correlation between each student's grade in the course and their PSVT:V score to find whether students with high spatial ability tend to be more academically motivated.

Although not measured quantitatively, it was noted that several students with PSVT:V scores that were a standard deviation above average were seen working in the laboratory on a regular basis, suggesting that students with higher spatial-visual abilities may be more motivated to perform in a class that utilizes these skills. MCMs were observed and analyzed during a two week period, and only students that were working in the laboratory were interviewed. A simple analysis was performed to find what percentage of students who took the test in each tier (lower, middle, and upper) were also interviewed. Again, the lower tier are the students who scored below one standard deviation below the average PSVT:V score, the middle tier are the students who scored between one standard deviation below and one standard deviation above the average PSVT:V score, and the upper tier are the students who scored above one standard deviation above the average PSVT:V score. These results are shown in Table 5.1

Table 5.1: Percentage of students who took PSVT:V test that were also interviewed

	Students interviewed	Students given PSVT:V test	% of Students interviewed and tested
Lower tier	3	27	11%
Middle tier	19	79	24%
Upper tier	12	28	43%
Total	34	134	25%

As can be seen from the table, the percentage of students that were interviewed in lab increased with increasing PSVT:V score. This may suggest that students with high spatial-visual skill are more academically motivated and spent more time working on their robots in lab.

5.4 Conclusions

A significant correlation between origami experience and high spatial-visual intelligence was found, suggesting that creating origami models can enhance one's spatial-visual reasoning. The correlation between the percentage of moving parts in a module and PSVT:V scores approached significance with a negative correlation. This may indicate that instead of creating more complex designs, students with high visual-spatial abilities may create more simple designs. It may be possible that students with high visual-spatial abilities are able to simplify more complex designs at an earlier stage of the design process than their peers, allowing them to eventually produce modules that have a smaller percentage of moving components.

Because no other significant correlations were found between spatial-visual skills and engineering design, no recommendations can be confidently made on whether universities should develop courses dedicated to improving these skills. Although research has found that spatial skills can be improved through instruction, the motivation behind developing these courses seems less clear, especially if other skills may be more important for engineering design. However, significant gender differences were found in this study, indicating that males may enter mechanical engineering design courses with stronger spatial-visual skills. Further research will need to be carried out based on the suggestions in the Future Work section in order to clarify the role of spatial-visualization skills in mechanism design.

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Chapter 6

Future Work

Although not possible within the time constraints of this project, the final grades students receive for the course and student performance in seeding rounds and the final competition should be correlated with PSVT:V scores. As explained in Section 5.3, this may take into account students that intentionally design simpler mechanisms that can more reliably score points during the competition. Correlating course grades with PSVT:V scores may also help discover whether students with stronger spatial-visual skills are also more academically driven than other students.

If the study were to be repeated, it would be helpful to have mechanism complexity and originality judged by a larger number of people. Only two people judged the mechanisms, so having a great number of evaluators would likely reduce error and biases.

Although no significant correlations between PSVT:V test scores and MCM complexity were found, it may be useful to see how PSVT:V scores vary among students in different academic fields. In Guay's research with the Purdue Spatial Visualization Test, the spatial skills of chemistry students were tested since these students need to use spatial skills to imagine 3D molecular structures [2]. It would be useful to find whether engineering students score higher on tests of spatial reasoning than students in majors that presumably do not utilize these skills to the same degree. A comparison between engineering majors and other majors such as architecture that may use spatial skills to the same extent may also lead to meaningful results. If engineers tend to score higher, this may suggest that students with high spatial-ability tend to pursue or thrive in engineering. If so, encouraging spatial-visual thinking in elementary school or high school may increase the number of students that choose to pursue an engineering degree in college.

Appendix A

Survey Forms

2/12/09
2.007 Pre-Test

Student ID # ______________________________

Gender : M F

Please rate your skill level based on the following scale:

(1 = no experience, 3 = basic experience, 5 = substantial experience)

	1	2	3	4	5
Sketching Skills					
Using CAD Programs (SolidWorks, AutoCAD, etc.)					
Building physical prototypes (woodwork, foam-core, etc.)					
Making origami figures					

You will have 10 minutes for this test. You are NOT expected to finish it.

Please do not discuss the test content with any other students following the test.

If you have any questions or concerns, feel free to email me at ttseng@mit.edu.

Figure A-1: Skill set survey

Directional Wheels, lateral motion, Defensive Robot

Student Name:

Lab Session:

Total # of Components

4 wheels, plates, 8×4=32 delrin, 2 delrin spacers.

38

Custom-Made Components

All of them

Moving Components

free spinning delrin wheels.

Planar/3D

rotational (3-axes).

% to completion

100% done

Originality (1-5)

Complexity (1-5)

6.829.

16

Figure A-2: Sample MCM data form

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