Investigation of Visual Spatial Ability and its Relation to Design Methods

by

Maria Prus

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

Bachelor of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2010

Signature of Author: ______________________________
Department of Mechanical Engineering
April 30, 2010

Certified by: ______________________________
Maria C. Yang
Assistant Professor of Mechanical Engineering & Engineering Systems
Thesis Supervisor

Accepted by: ______________________________
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

THIS PAGE INTENTIONALLY LEFT BLANK

Investigation of Visual Spatial Ability and its Relation to Design Methods

by

Maria Prus

Submitted to the Department of Mechanical Engineering
on April 30, 2010 in partial fulfillment of the
requirements for the degree of

Bachelor of Science in Mechanical Engineering

Abstract

The purpose of the study was to determine if a significant correlation exists between visual spatial ability and the construction of both two and three dimensional models and previous experience using the skills involved in these two subset subject areas of engineering prototype design. Mechanical engineering undergraduate seniors were given a spatial intelligence test known as the Paper Folding Test, a 6 minute test created by the Educational Testing Service. They were also asked to create an origami figure given a set of instructions lacking any written description, only images of the paper folds and rotations. This test will be timed and the length of time to complete the origami task will be compared to the student's scores on the Paper folding test and to their self reported experience levels in CAD, sketch model, and origami figure creation. The participants were also asked about the difficulty or ease they experienced completing each test. A significant correlation existed between the scores on the Paper Folding Test and the origami exercise completion times. Subjects with the fastest origami figure completion times tended to receive a higher score on the Paper Folding Test. Additionally, subjects with more than basic origami experience correlated significantly with receiving higher scores on the Paper Folding Test. No other correlations between previous experience and test score success were determined significant.

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

THIS PAGE INTENTIONALLY LEFT BLANK

Acknowledgements

I would like to thank Professor David Wallace for allowing me to advertise my study on the 2.009 course email list. Additionally, I would like to thank the individuals who took the time out of their busy schedules to participate in my study. Lastly, I would like to thank Professor Maria C. Yang for her valuable advice, encouragement, and guidance throughout the process.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

1 Introduction

Spatial intelligence is a key skill used by engineers, architects, and artists during the design process, and is taught in a range of mechanical engineering courses. Spatial intelligence can be defined as the cognitive ability to distinguish and manipulate patterns. There are many written standardized tests for visual spatial ability, but it is unclear if tasks involving mental rotation of forms presented on two dimensional paper translate to the physical construction of three dimensional models. Today, despite the frequent use of CAD in both architecture and engineering disciplines, three dimensional physical model making is still used as a key tool in design, such as sketch models for engineers and scale models for architects. Learning from a physical prototype can be very different from working with sketches or two dimensional depictions. In fact, the discovery of the double helix structure for DNA was based off of a physical three dimensional model, as the visualization was a different way of thinking and a more appropriate approach to discovering this complex layout [1]. The purpose of the study was to determine if a significant correlation exists between using visual spatial ability to construct two dimensional and three dimensional models and previous experience using the skills involved in these two subset subject areas of engineering prototype design.

Mechanical engineering undergraduate students in their senior year, who have had experience both in constructing sketch and CAD models in the undergraduate design curriculum, were presented with two simple tasks representative of the aforementioned differences in visual spatial ability. To simulate CAD modeling or two dimensional on-screen design, the Paper Folding Test for visual spatial ability was utilized. For three dimensional or sketch model construction, the creation of a simple origami figure from image-only directions was used.

The implications from the study of correlation between two and three dimensional prototyping and experience could mean the extension of engineering design curriculums to include more detailed instruction for students on how to develop their visual spatial abilities. Broader implications of the study may help instructors improve their understanding of the overall role of visual spatial skills in design.

2 Background

2.1 Visual-Spatial Ability

2.1.1 Definition

Spatial intelligence can be defined as a person's ability to distinguish and manipulate objects in one-dimensional or multi-dimensional space [2]. This ability is often used when designing mechanisms or products, as engineers must mentally or physically move and combine parts to ensure the optimum orientations and functions of each part within the overall structure of the imagined device. Often visual spatial ability is evaluated using standardized tests such as the Paper Folding Test, which was the test selected as an indicator of visual spatial ability in two dimensional reasoning for this particular study.

2.1.2 Paper Folding Test

The Paper Folding Test (PFT) is a standardized test issued by the Educational Testing Service to evaluate a person's visual-spatial ability. The test measures the ability of a person to mentally flip and fold a piece of paper according to the directions provided. At the end of the folding sequence, a hole is punched through the paper. Not only must the person be able to visualize the folds, but he must also remember how to unfold the paper to correctly identify the location of the holes on the original unfolded sheet.

The PFT consists of twenty multiple choice questions spread out over two pages. In three minutes, the test taker must complete ten questions, with three additional minutes and ten more questions given on the second page. The questions become more complicated as the page continues, so it is necessary to work efficiently from the start. Each question presents a series of images which begin with a single fold. For every additional fold that the paper has, a new image is shown in the sequence. The final image depicts the paper with a hole punched through it, and the test taker must mentally unfold the paper to determine how many holes are present and where their placement would be on the original sheet. Then the test taker is presented with five multiple choice answers, with each answer choice showing holes in the paper in different configurations. An example problem that was shown to all test takers before completing the timed and graded portion of the test is shown below in Figure 2-1. The paper is never rotated or turned in any way during the PFT, and each new fold is represented with a new image in the sequence.

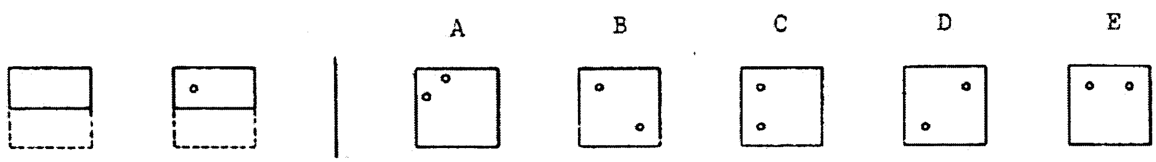

Figure 2-1: Paper Folding Test Example Question [3]

2.2 2.009: The Product Engineering Process

All students who participated in the study were seniors who had taken 2.009 during the fall semester. These students were chosen because of their exposure to the key design methods taught in the class, and their participation in the study did not affect their grade for the course. Most mechanical engineering undergraduate students choose 2.009 as their senior design project class. In the course, students are given a broad theme and are asked to create a prototype of a new product by the end of the semester. The theme for Fall 2009 was Emergency, so products had to be useful in an emergency situation. Many of the initial weeks of the course are used for idea generation and testing product concepts before selecting a final project to continue with for the last part of the semester. Each project team consists of sixteen students, though in the earlier part of the semester these teams were subdivided into two teams of eight to develop and test ideas before committing to the final product.

The course structure is broken up into different milestones that occur every two or three weeks throughout the semester. After brainstorming ideas that satisfy the project theme, the students are asked to do some initial research and to present their three favorite ideas. Based on the presentations, the course instructors provide each team with a sub-category of the theme, which is still broad but helps to guide new product ideation. From there, two ideas are investigated by building sketch models, or simple physical models that demonstrate a key function of the product. Teams then decide on a single idea to pursue for the mockup review, where a critical or most challenging function of the product's feasibility is demonstrated. Now a final product is chosen by the group and only six weeks remain to build a functioning prototype. There are various check points along the way such as the assembly review, where CAD models are presented, and the technical review, which shows most if not all of the working prototype in action. Specific milestones that relate to visualization are the creation of sketch models and the assembly review CAD renderings. Because of the experience the test subjects have with these milestones, the subjects were well prepared to tackle the visual evaluation tasks associated with the study.

2.2.1 Sketch Models

A quick first method for testing a design idea is to create a sketch model. Sketch models are simple physical models created from easily acquired materials such as foam or cardboard. They help demonstrate a key feature of the design so that future versions of the design can include the information learned from the demonstration. For example, one could test different shapes for a product casing by cutting them into foam and having users interact with the foam to see what is most comfortable or natural for the user. This feedback is valuable and cannot be gathered from a drawn 2D sketch or CAD model, where users cannot touch or interact with the design concept. Another use for sketch models is to test the overall product concept before being concerned with form. One great example of a sketch model that was quickly put together to test a product concept for 2.009 was for a vibrating ice scraper. The team connected a motor to an existing ice scraper head and tested whether it was easier to remove ice from a surface with the additional force generated by the motor than manually.

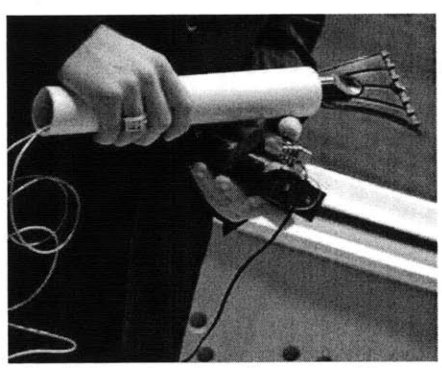

Figure 2-2: Sketch Model of a Vibrating Ice Scraper, Presented by Silver Team during the Sketch Model Review [4]

2.2.2 CAD Models

Another design strategy is the use of CAD modeling. With a three dimensional modeling software package like Solidworks, one can arrange different parts in an on-screen assembly without ever having the parts in hand. Using the software, one can help guide the design process and create a shared, detailed vision for how the product will appear. Another advantage of CAD modeling is that from the solid part, drawings and manufacturing instructions can easily be created on screen and printed to help communicate the product vision. Parts can also be fabricated directly from either the drawings or the 3D model itself using machines such as the waterjet or 3D printer. During 2.009, all team members were required to model a part in Solidworks for their product assembly CAD model. An example of a CAD model for the vibrating ice scraper can be seen in Figure 2-3 below.

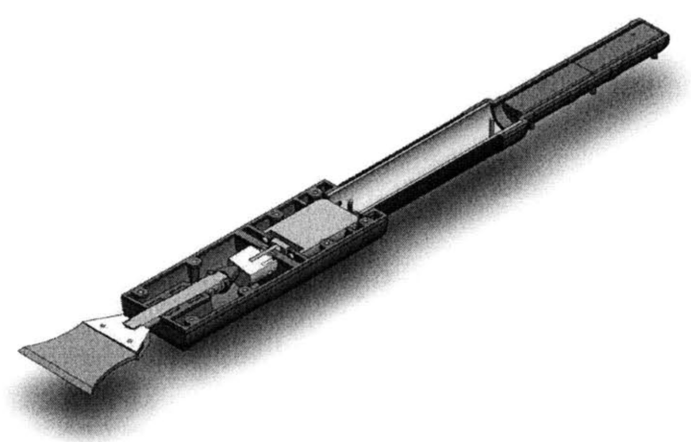

Figure 2-3: CAD Rendering of Vibrating Ice Scraper [5]

2.3 Origami

Origami is classified as an activity that stimulates the visual spatial area of our brains. Construction of origami figures was chosen as the sketch model representative because most people have had some exposure to this three dimensional construction activity, similar to the subjects who had all taken 2.009 and had to create a physical sketch model for their product idea. The ease of access to folding patterns online and availability of origami paper in craft stores was also a benefit to choosing this activity for the study. When looking for an appropriate folding pattern for the study, it was important to consider the difficulty level of the exercise so that it was not too difficult for the beginners yet not too simple for experienced persons. Many different folding patterns were investigated before the final selection, including multiple versions/image directions for the same final product. Each personal trial was timed to note the relative difficulty ratings of the possible patterns. In the end, the open box folding pattern was chosen (see Figure A-1 in the Appendix), which all subjects reported as a pattern they had never folded before, despite their origami experience levels.

2.4 Statistical Analysis

To determine if a correlation exists between the exercise scores and other data collected, the Spearman ranking correlation was used. The equation to determine the Spearman ranking coefficient, r_s, is given in Equation 2.1:

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

The difference between the ranked variables x_i and y_i is denoted as d_i, and n represents the number of raw scores. Positive and negative correlations are determined by the sign of r_s, with a value between 0 and 1 indicative of a positive correlation and a value between -1 and 0 indicative of a negative correlation. Significance was determined using the t test. The Student's t distribution function for a data set with n-2 degrees of freedom is as follows:

$$t = r_s \sqrt{\frac{n-2}{1-r_s^2}} \qquad (2.2)$$

Once the t value is calculated, a t table is used to see which confidence range the t value fits in. For this study, results were considered significant above a 90% confidence level.

THIS PAGE INTENTIONALLY LEFT BLANK

3 Methodology

Ten mechanical engineering undergraduate seniors were given the Paper Folding Test and a timed origami exercise without any written instructions in the same sitting. The length of time to complete the origami task was compared to the student's scores on the Paper folding test and also to their self reported experience levels in a survey.

3.1 Paper Folding Test

The Paper Folding Test (PFT) was administered to each subject after they completed the pre-experiment survey question regarding their previous experience with creating CAD models, sketch models, and origami figures. After the subjects read the introduction and example page, they were asked if they understood the directions and had the opportunity to ask for clarification before starting the timed portion. There were two pages with ten questions on each page, and three minutes were given for the completion of each page. Subjects' scores did not affect their final grades in 2.009, the class prerequisite for the study. Following the guidelines recommended by the Educational Testing Service, scoring was performed by marking one point for each question answered correctly, zero points for each question not answered, and minus a half point for each question answered incorrectly to discourage random guessing. The highest score one could receive on the test was twenty points.

3.2 Origami Exercise

Subjects were informed before they began the origami exercise that they would be timed while completing the origami exercise. The origami exercise consisted of twelve steps with the text removed from each step so that only the images were available for directions. Images were presented in four rows of three steps each, which can be seen in Figure A-1 in the Appendix. Subjects were informed of the layout of the directions before they began so that they would not get confused during the exercise.

3.3 Self Evaluation Survey

The self evaluation survey was useful to asses the previous experience each subject had in different areas. Before the two exercises were given, subjects were asked to rate their experience level with creating sketch models, CAD models, and origami (see Figure A-2 in the Appendix). For each of these activities, a scale of 1-5 was used to rate experience, with 1 indicating no experience and 5 indicating substantial experience. After completing the exercises, subjects were asked to rate the difficulty of each exercise using a similar 1-5 scale, with 1 indicating the task was very easy and 5 indicating the task was very difficult. These rankings were considered when evaluating the results from both the PFT and origami exercise. Additionally, participants were asked if they had previously constructed the origami box from the origami exercise.

4 Results

4.1 PFT Test Scores

The most frequent number of questions answered was 18 out of 20, with four of the ten subjects completing this number of questions. The histogram below in Figure 4-1 shows the distribution of the number of questions answered for all ten subjects.

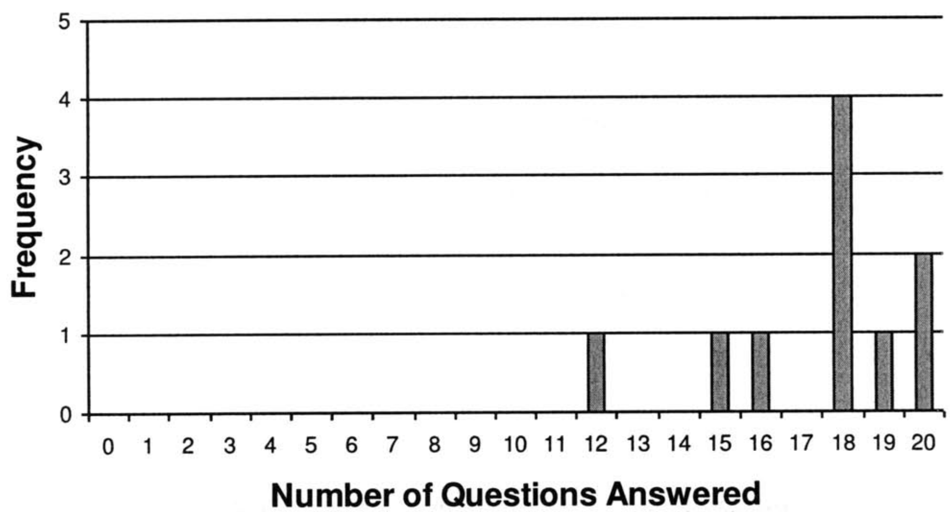

Figure 4-1: Histogram of Number of Answered Questions (n = 10)

Subjects who answered fewer questions tended to score the lowest on the PFT. No subject received a perfect score on the test, and certain questions were skipped or missed more often than others. The scoring results can be seen in the histogram in Figure 4-2 below.

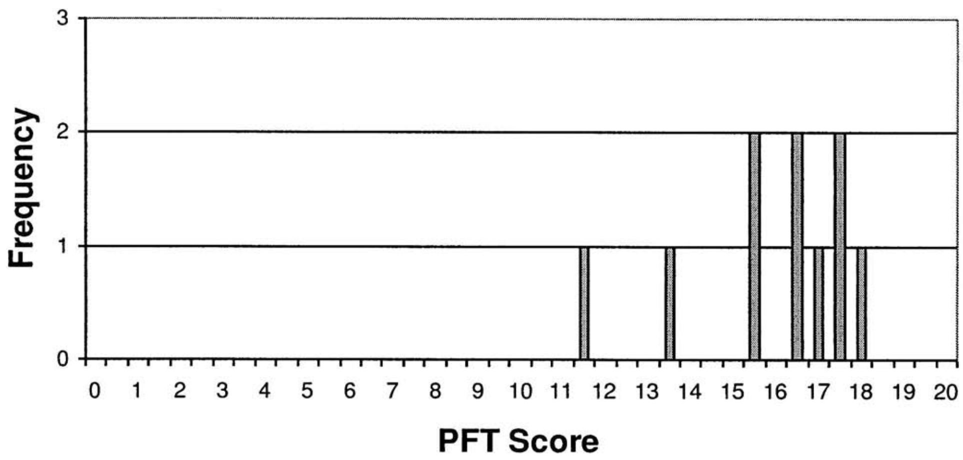

Figure 4-2: Histogram of Paper Folding Test Scores (n = 10)

It is commonly known that two standard deviations above or below the mean is statistically insignificant. However, excluding the lowest score because it is slightly outside of this range seemed inappropriate, given that it represented ten percent of the data and the corresponding origami results were well within two standard deviations. Additionally, since the confidence level for the correlations is defined at 90%, and two standard deviations above or below the mean is representative of 95% confidence levels, then it is still appropriate to include the lowest PFT score when analyzing results.

4.2 Origami Test Results

The time it took each subject to complete the origami task ranged from about three minutes to almost twelve minutes. Almost all of the subjects who completed the task perfectly had the quicker times. Figure 4-3 below shows a sample of three constructed boxes that were perfectly matched to the likeness shown in the directions, meaning the box was square, could sit naturally without unfolding, and was the same color for the entire visible portion of the box.

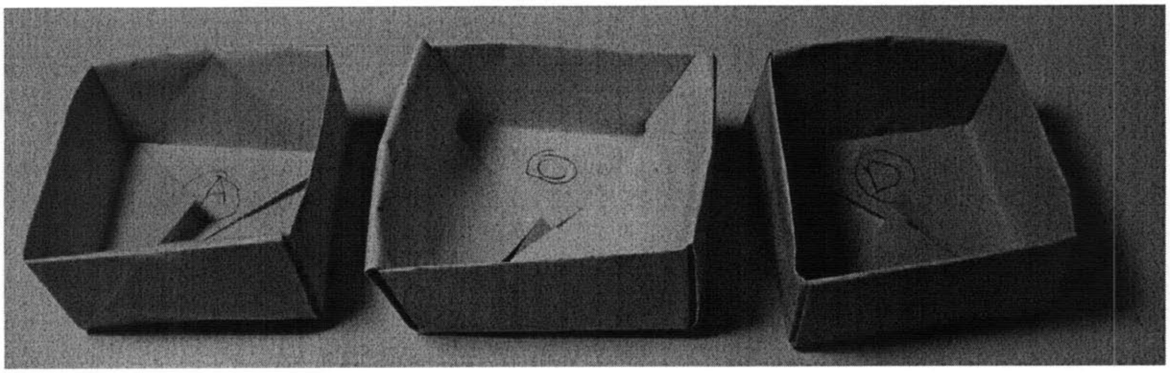

Figure 4-3: Successful Origami Boxes

Not all subjects completed the origami task perfectly. Participants were allowed to stop the origami exercise after a significant effort was put into understanding the directions and they felt the box was completed to the best of their ability. Each of the three example boxes below represent the most trouble people had with the exercise and likewise the completion times were all above average.

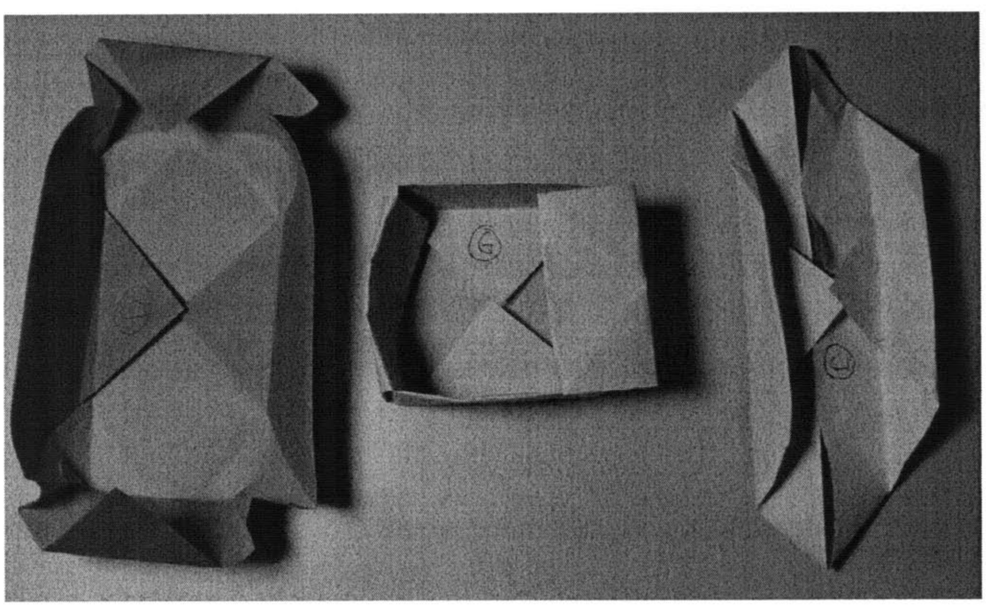

Figure 4-4: Imperfect Origami Boxes

4.3 Survey Results

All subjects reported that they had never constructed the origami box project, despite varying degrees of origami experience. Overall, people were least experienced in origami and found the PFT less difficult than the origami exercise. A summary of the results is presented in Table 4.1 below.

Table 4-1: Pre and Post Experiment Survey Question Results Summary

Survey Question	Average	Standard Deviation
CAD Skill	3.1	0.74
Sketch Model Skill	3.2	0.92
Origami Skill	2.7	1.25
PFT Difficulty	2.5	0.85
Origami Difficulty	3.1	1.20

In terms of significant correlations between reported experiences and difficulty levels and experimental results, two values were shown to be significant using the t table method described in section 2.4. For the PFT scores, it is noted that significant origami experience correlated with higher PFT scores with a confidence rating of over 99%. Longer origami figure completion time correlated positively with the post-experiment ratings of the origami exercise as more difficult. This value also has a confidence rating of over 99%.

4.4 PFT and Origami Test Results

A significant correlation exists between the experimental results of the PFT and origami test. The Spearman correlation was determined to be -0.57, indicating that the time to complete the origami exercise tends to decrease when the score on the PFT increases.

The t test gave a t value of 2.0, which is found between the 90% and 95% confidence range on a two tailed t table with eight degrees of freedom. A scatter plot of the PFT scores with the corresponding origami completion time is presented below in Figure 4-5.

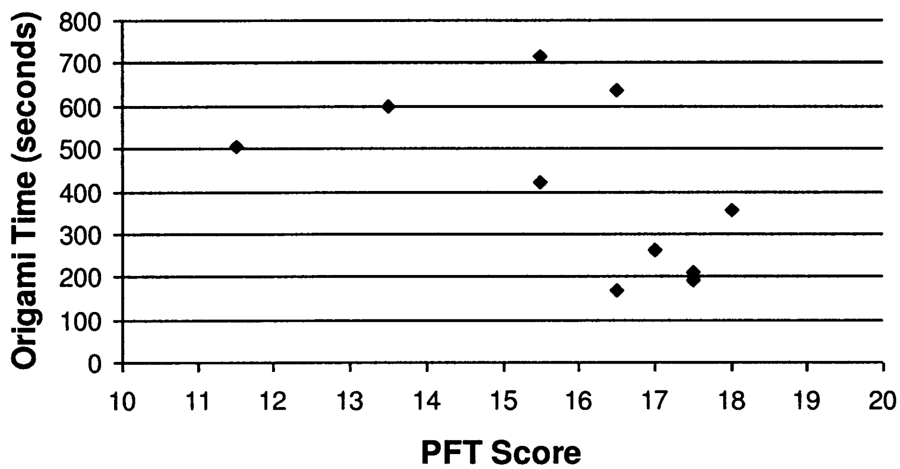

Figure 4-5: Origami Time in seconds versus PFT Score

THIS PAGE INTENTIONALLY LEFT BLANK

5 Discussion

5.1 PFT Test Scores

The PFT test scores were usually over 75% correct, showing that the visual spatial skills the subjects were assumed to have acquired through 2.009 were indeed present. A few questions in particular were commonly missed or skipped. These questions had a particular theme to them, involving folds that took a rectangle or triangle into a trapezoid by folding along the diagonal. This may be an indication of the natural visualization process of the brain that these challenges questions involved this specific fold, or perhaps it shows a limitation on the visualization techniques that we are traditionally exposed to in an engineering design curriculum.

Surprisingly, only one subject out of ten used a pen to occasionally mark the supposed placement of the holes punched on the test paper itself. It should also be noted that this subject had one of the highest scores on the PFT. This was a visualization strategy that I had used frequently when taking the PFT before completing the run of the study. Perhaps this observation is an indication that the other participants were not aware they could write on the test, or that this visualization strategy was not apparent to them as a natural way to solve the problem. Adding specific visualization strategies to a design curriculum could improve problem solving efficiency.

5.2 Origami Test Results

The origami test results had a large variation in completion time based on the subject. This could be seen as positive as correlations between speed and PFT scores were clear. However, what is unclear is if the test was truly representative of the ultimate goal, as the format of the instructions on multiple lines may not have been the natural way to organize the directions. A few times during the test it seemed people were confused when they had to skip from the end of one line to the beginning of the other. This was especially true with the jump from step 9 to step 10, which was the critical step for transforming the two dimensional pre-folded piece to a three dimensional box wall. The people who took ten minutes or more to complete the exercise generally were on pace for a quicker time until they reached step 10, and spent a majority of the time trying to rationalize its meaning. One cannot for certain say that it was a poorly designed direction for this critical step because many people could complete the step without issue. However, it is unknown if the step was portrayed differently that more people would have finished with quicker times.

It is also important to note that many people did not notice the origami exercise directions lacked words, which is probably another reason why many people struggled and asked questions during the complicated step 10. However, as noted above, step 10 was the critical step that turned the two dimensional paper to a three dimensional box, so the struggle could also be related to the sudden transition from two to three dimensional visualization.

5.3 Survey Results

For the most part, no statistically significant correlations between the survey data and visualization data existed. It is possible that the lack of correlation is related to people's ability to evaluate their skill levels accurately. If there were standardized tests to measure each person's skill level in CAD modeling, sketch modeling, etc, then perhaps a stronger correlation would have been present. Another important thing to note is the survey asked for the self reported experience level for each activity, which can be different from a person's actual ability in that subject area.

A few survey points were statistically significant to test results. People accurately reported that the origami exercise was difficult if they took a longer amount of time to complete it. This is logical because people were aware that they were struggling as they in theory had an infinite amount of time to complete the exercise. It was not noted that people who felt the PFT was difficult did worse on average, or vice versa. This is a more accurate representation of self reporting because the subjects are unaware of their progress past the total questions answered in the given amount of time.

The other statistically significant point that the survey connected to the test results was the correlation between high PFT scores and significant previous origami experience. The two dimensional folds in a series of images on the PFT were very similar to origami folding steps without text, so if one has previous experience utilizing this visualization method, then the connection between the two values is clear. Interestingly, one would think there would have been a higher correlation between previous origami experience and the speed of completing the origami test, but the significance of this correlation was outside of the 90% confidence range and thus can not be cited as a valid experimental result.

5.4 PFT and Origami Test Results

There was a significant correlation between the results of the two exercises that subjects completed. The time to complete the origami exercise tended to decrease with an increasing score received on the PFT. People who tended to succeed at the PFT were also likely to succeed in creating the origami figure in the least amount of time. Because of the relationship between the exercises in terms of utilizing similar visualization techniques, this result is expected.

5.5 Conclusions

Since no significant correlations existed between visual-spatial ability and experience with different design and prototyping strategies, no recommendations can be made with confidence on the need for students to develop their visual-spatial ability to improve design prototyping methods. It is possible that other techniques for engineering design may be more important to expose students to as they learn about the design process. Further research would need to investigate a student's measured or graded success with design prototyping methods like CAD and sketch models and compare it to standardized tests for visual-spatial ability. It would also be relevant to investigate the role of gender in visual spatial ability and design success. However, in this study, the gender sample sizes were too small to illustrate trends for either males or females.

THIS PAGE INTENTIONALLY LEFT BLANK

6 Appendix

Figures

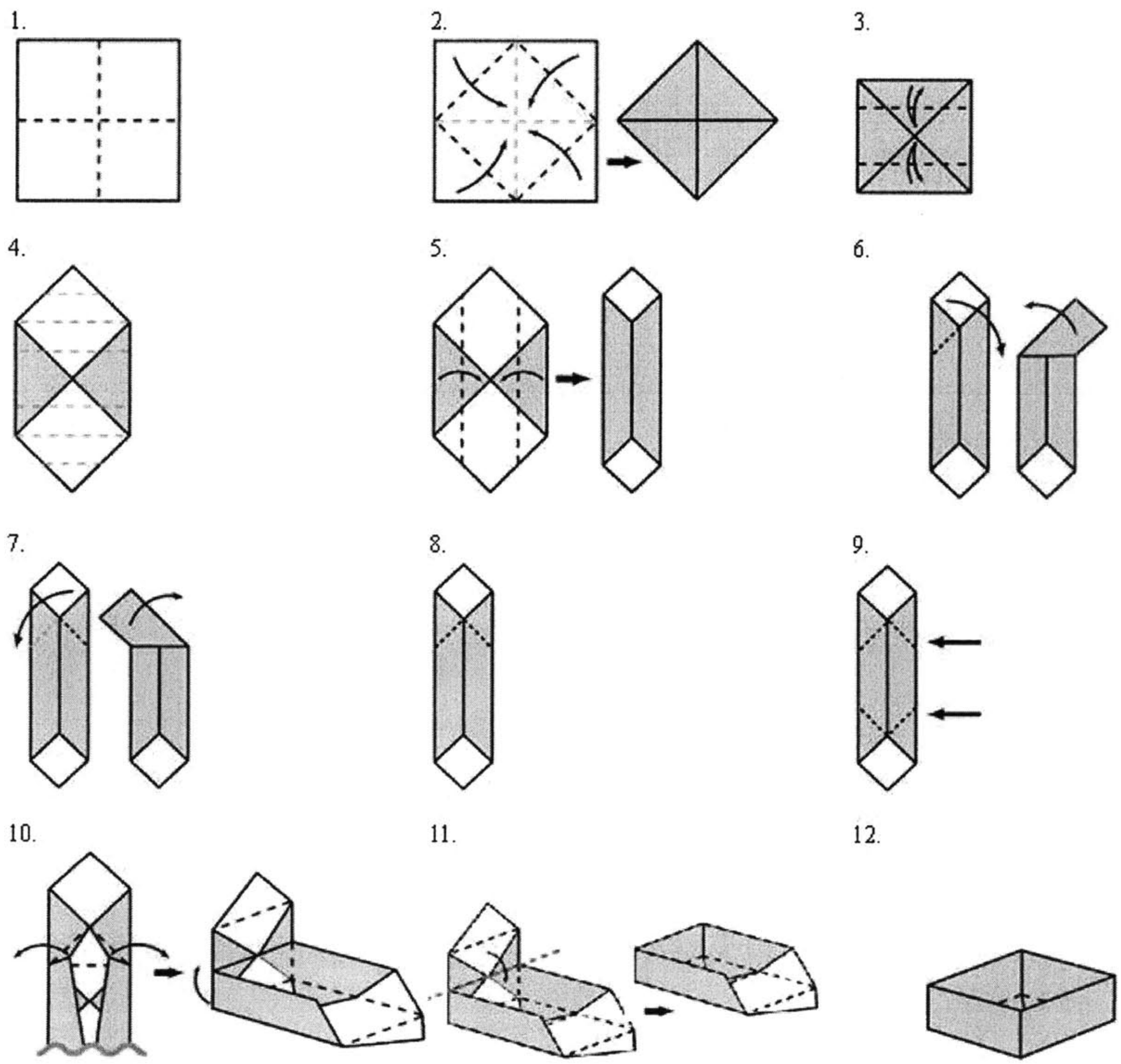

Figure A-1: Origami Exercise [6]

Experience Survey
Test ID ________

Pre-experiment

Please rate your experience in the following skills on a scale of 1-5 with the following numerical definitions:

1 No experience
2 Little experience
3 Basic experience
4 Reasonably experienced
5 Substantial experience

CAD software (ex: Solidworks)	1	2	3	4	5
Sketch Model creation	1	2	3	4	5
Origami figures	1	2	3	4	5

Post-experiment

Please rate the difficulty level for completing each experiment on a scale of 1-5 with the following numeric definitions:

1 Very easy
2 Somewhat easy
3 Moderate
4 Somewhat difficult
5 Very difficult

Paper Folding Test	1	2	3	4	5
Origami Figure Construction	1	2	3	4	5

Have you previously constructed this particular origami figure before? (Circle the best answer)

Yes, once or twice
Yes, more than a few times
No, never

Figure A-2: Pre and Post Experiment Surveys

7 Bibliography

[1] R. H. McKim. *Experiences in Visual Thinking*. Second Edition. 1980. pp. 10.

[2] T. Tseng. Spatial-Visual Skills and Engineering Design. 2009.

[3] Paper Folding Test. Educational Testing Service. Spatial Intelligence Learning Center. http://spatiallearning.org/resource-info/Spatial_Ability_Tests/Paper_Folding_Test.pdf

[4] Sketch Model of Vibrating Ice Scraper. 2.009 The Product Engineering Process: Silver Team. http://web.mit.edu/2.009/www/grading/sketchModelReview/sketch_silverB.html

[5] CAD Rendering of Vibrating Ice Scraper. 2.009 The Product Engineering Process: Silver Team. http://web.mit.edu/2.009/www/grading/assemblyReview/silver/imageslarge/assembly2.jpg

[6] Origami Box Instructions. Origami Fun Website. http://www.origami-fun.com/origami-box.html