Improving Spatial Reasoning Ability While Learning Energy Efficient Construction: Students Who Build Physical Models vs. Students Who Develop 3D Computer Models

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Abstract: Olkun defines spatial reasoning as “the mental manipulation of objects and their parts in 2D and 3D space.” In a previous study, the author found that physical model building increased student spatial reasoning by 12% on average, as compared to drawing the same topic as an axonometric drawing. To further this study, this paper will examine the effect of two different types of model building exercises – student-built physical models and student-produced computer graphic 3D models – on the development of students’ spatial reasoning in freshman non-design courses. Model building is currently not part of the course curricula in the non-design courses at our institution. In this study, a section of freshman architecture and construction management students is divided into two groups. Each group is given a spatial reasoning ability pre-test. One group is then assigned to build scaled energy efficient framing models (physical models), while the other group is asked to develop 3D computer graphic models of a residential structure. At the end of the semester, both groups are given a spatial reasoning ability post-test and a qualitative survey. Each student’s spatial reasoning ability pre-test result is compared to their post-test result to determine how the physical or graphic model project effects their spatial reasoning ability. The results of the quantitative and qualitative tests in this study will provide faculty with an understanding of the relative benefit of implementing one or both of the model building exercise types in their non-design courses.

Index Terms: Spatial, Physical, Computer, Models

I INTRODUCTION

Olkun defines spatial reasoning as “the mental manipulation of objects and their parts in 2D and 3D space.”[1] In a previous study, the author found that physical model building increased student spatial reasoning by 12% on average, as compared to drawing the same topic as an axonometric drawing. To further this study, this paper will examine the effect of two different types of model building exercises – student-built physical models and student-produced computer graphic 3D models – on the development of students’ spatial reasoning in freshman non-design courses.

II BACKGROUND

For engineers, architects and many others in the science, technology, engineering and mathematics fields (STEM), spatial reasoning ability is threaded throughout day-to-day practice. Designing buildings, sites, roadways, bridges, chemicals and products, the design professional needs to understand 3-dimensional (3D) objects. This includes how 3D objects are viewed in component form (exploded and progress construction views), sections, plans, rotations and a variety of views (such as perspective, walk-through and shade and shadow). A National Science Foundation (NSF) report titled “Preparing the Next Generation of STEM Innovators” mentions spatial aspects twice in the following statement: The capabilities of STEM innovators often include “mathematical and spatial abilities alone or in combination with verbal aptitude, along with other factors such as creativity, leadership, self-motivation, and a diligent work ethic. In an increasingly technological society, innovation is frequently an interdisciplinary endeavor and many traditional non-STEM fields require scientific, spatial, and quantitative talents.”[2] However, in past years spatial reasoning is not generally taught in our K-12th grade schools. Some have speculated that the reason for this may be the fact that those drawn to education are generally stronger in reading, writing and math and therefore place higher regard on these areas, that spatial reasoning ability is more vocational in nature and not held to the same esteem as theoretical subjects and careers, or that it costs more to train spatial reasoning ability due to the need for more hands-on teaching resources.[3,4] Therefore students arrive in architecture, engineering and all STEM

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programs with little or no exposure to spatial visualization training. Yet they are expected to think and communicate spatially. The students who do start our programs with stronger spatial skills may have picked it up through building and taking apart objects as children, eg Lego® and K'Nex®, which stereotypically has been marketed for boys, thus giving males the edge in this area[5]. As an aside it is interesting to note that Lego has recently introduced a whole line of their products aimed at girls called "Lego Friends," so the tide may be changing.

Not only are students entering third level education, and particularly architecture and engineering programs, with limited spatial reasoning skills but hands-on resources such as construction labs may have been replaced by the more cost-efficient computer labs that are used for a number of courses.

Student-built computer models have many benefits in engineering and architectural education such as being cost effective, easily shared and stored electronically, the ability to manipulate and change models and parts quickly. Building physical models has benefits that are not possible in computer model building: physical models can be picked up and examined, they appeal to kinesthetic and visual learning styles, and like the structures our students will be developing in their professional careers – they are real. Also it must be noted that photographs of physical models can be easily shared electronically and depending on how the model is constructed, it may be easily changed, although not as easily as computer models can be changed . Physical model building may be more costly to the student if they have to buy the supplies, and storage of multiple years of physical models may be an issue for the institution.

While there is a variety of literature on spatial reasoning and physical models, few studies have compared the effect of integrating student-built physical models or student-prepared computer models on students' spatial reasoning abilities. Harris et al noted that biology students who had used physical models and molecular imaging programs together over several weeks "produced higher quality answers to certain higher-order questions than students who only used computer imaging programs during the same time period." [6] Kuo et al found that student-produced computer models had an advantage over student-prepared flat or perspective drawings in 2-dimensions (2D). They also noted that students who built computer models perceived this type of project as more difficult to work with than hands-on models. [7]

Many years ago our institution had a building lab where architecture and construction technology students would learn construction techniques by building 1:1 scaled structures in a lab. It is reported that the students and faculty used to build a house each year in this lab course. Over the years, this lab was removed and our programs became less "hands-on" and more theoretical. Physical model building, at greatly reduced scales, and funded by the individual student or student teams, remained in many design courses taken by architecture engineering technology students but not a required in the construction management engineering technology program. As the years progressed, computer models replaced physical model building in half of our design courses. Similar to many engineering and architecture programs across the United States, my institution replaced physical model building with computer-generated models. At the same time the spatial reasoning ability of the same groups of students has been reported to need improvement. Seeing this as a problem, many colleges and universities have started to test incoming students in spatial visualization skills, implemented a separate course for those that need to develop this skill or integrated spatial strategies into existing courses.[8] But another or additional way to look at this is to ask will returning student-built physical models to our existing curriculum improve students' spatial reasoning ability? The goal of this paper is to test the effect of physical model building against virtual model production on students' spatial reasoning ability in 2 non-design courses.

In a prior study[9] , funded by a Title III Students First grant, the author tested the spatial reasoning ability of students also in 2 non-design engineering technology courses. A model building project was integrated into each freshman course to encourage active learning and to improve spatial reasoning. One group of students built a physical model and a second group of students prepared an axonometric of the same construction technique – a light wood framing building corner. Manual model building was tested against manual drafting. Both groups of students were given a spatial reasoning pre and post-test. This study found that the students who built the physical models improved their spatial reasoning ability on average 12% more than that of students who had prepared manual axonometric drawings of the same construction technique. This present study will examine hands-on physical model building against "hands-on" computer models. The spatial reasoning test used in the first test was the Fibonicci Spatial Reasoning Test[10] and the test performed in this present study is the Purdue Spatial Visualization Test. Both use similar criteria for the different areas of spatial reasoning.

III FIBONICCI SPATIAL REASONING TEST AND PURDUE SPATIAL VISUALIZATION TEST

The Fibonicci Spatial Reasoning Test and the Perdue Spatial Visualization Test are similar in question type. The Fibonicci test is a 20 question spatial reasoning aptitude test that has questions from each of the 3 spatial visualization areas – developments, rotations and views in 1 test.[11] ThePurdue Spatial Visualization Test (PSVT)[12] consists of 36 spatial reasoning questions in total separated into 3 parts, each part containing 12 questions: Developments, Rotations and Views. The Fibonicci test is available at no cost online. There is a small charge for the PSVT. The PSVT was used in this study as it has been has been used widely as a test in educational and workforce settings since 1976. The following is a brief explanation of each of the 3 spatial reasoning areas tested:

Developments

Figure 1 is a sample of the Developments section of the PSVT. It tests how well a candidate can visualize the folding of flat pieces of paper into 3-D objects.

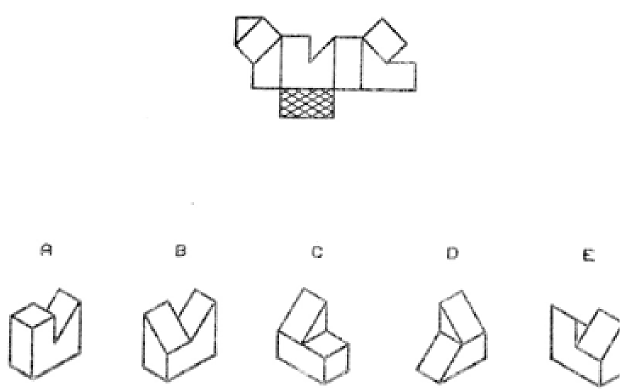

Fig. 1

Rotations

Figure 2 is a sample of the PSVT Rotations section. It tests a candidate's ability to visualize the rotation of 3-D objects.

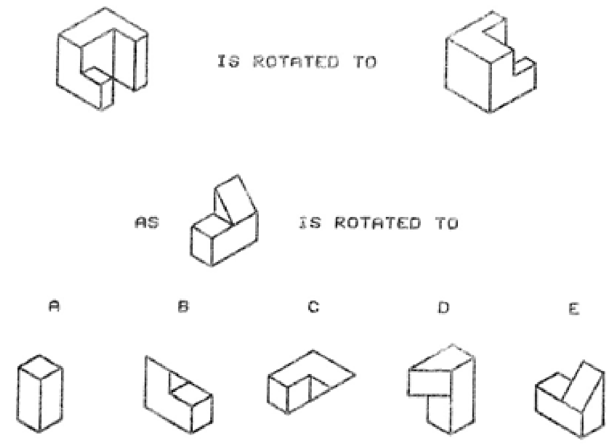

Fig. 2.

Views

Figure 3 is a sample of the Views section of the PSVT. It tests how a candidate understands what an object looks like from different views.

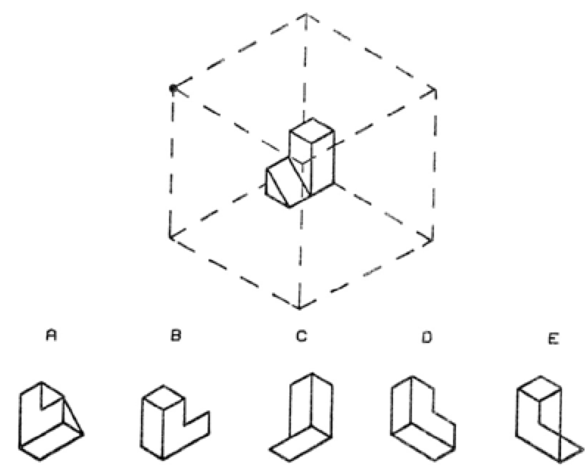

Fig. 3.

IV TEST METHODOLOGY

As part of a Title III Students First grant to integrate sustainable construction techniques into construction courses through project-based learning, the author integrated student-built physical or virtual model projects into 2 different non-design freshmen courses. One course is manual drafting and the other is computer drafting. Both of the groups had completed a manual drafting project prior to the model building projects, so they were both equally familiar with the basics of plans, sections, elevations and axonometric drawings. Each course contained 20 different students from both the architecture and construction management engineering technology programs within our institution. The physical model group had 4 females and 16 males, and the computer model group had 3 females and 17 males. Both groups were given the Purdue Spatial Visualization Test as a pre-test to assess their spatial reasoning ability prior to building their designated model. One group was then assigned to build a residential framed physical model as a project to be completed outside of class and submitted at the end of the semester, while the other group was assigned to develop a 3D computer graphic model of a residential structure using AutoCAD Architecture and Revit Architecture computer programs. The computer group worked on their 3-D computer assignment in class and outside of class. Both groups had the same overall time duration to build their models 8 weeks. At the end of the project, both groups were once again given the Purdue Spatial Visualization Test as a post-test, and they were also asked to complete a short qualitative survey. Each student's spatial reasoning ability pre-test results were compared to their post-test results to determine if the physical or 3-D computer graphic model project affected their spatial reasoning ability.

V RESULTS

The 3 sections of the Purdue Spatial Visualization pre and post-tests – Developments, Rotations and Views – were each scored separately to pinpoint the potential area(s) of student spatial reasoning that benefited, or had not benefited, from building a physical model or computer model.

First, each group's pre-test results were compared to their post-test results for each of the 3 areas (Developments, Rotations and Views) to see whether there was a statistically significant change in each student's spatial reasoning ability. The results were as follows:

Quantitative Results: Student-built Physical Model Group:

TABLE 1
DEVELOPMENTS: NO PROVEN CHANGE

Development (Dev) Tests – Physical Model
t-Test: Paired Two Sample for Means

	Dev. Pre-test	Dev Post-test
Mean	9.15	9.55
Variance	6.87	7.63
Observations	20	20
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	-1.02	
P(T<=t) one-tail	0.16	
t Critical one-tail	1.73	

TABLE 2
ROTATIONS: PROVEN IMPROVEMENT

Rotations Tests – Physical Model
t-Test: Paired Two Sample for Means

	Rotations Pre-test	Rotations Post-test
Mean	8.10	8.90
Variance	7.15	7.46
Observations	20	20
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	**-2.10**	
P(T<=t) one-tail	0.02	
t Critical one-tail	1.73	

TABLE 3
VIEWS: PROVEN IMPROVEMENT

View Tests – Physical Model
t-Test: Paired Two Sample for Means

	Views Pre-test	Views Post-test
Mean	4.55	7.50
Variance	11.94	13.4
Observations	20	20
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	**-2.69**	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.73	

Student-built 3D Computer Model Group:

TABLE 4
DEVELOPMENTS: NO PROVEN CHANGE

Developments (Dev.) Tests – 3D Computer Model t-Test: Paired Two Sample for Means		
	Dev. Pre-test	Dev. Post-test
Mean	7.85	8.00
Variance	12.66	12.00
Observations	20	20
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	-0.24	
P(T<=t) one-tail	0.41	
t Critical one-tail	1.73	

TABLE 5
ROTATIONS: PROVEN DETRIMENT

Rotations Tests – 3D Computer Model Group t-Test: Paired Two Sample for Means		
	Rotations Pre-test	Rotation Post-test
Mean	8.15	7.20
Variance	8.34	10.38
Observations	20	20
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	**1.84**	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.73	
P(T<=t) two-tail	0.08	

Table 6 – Views: No proven change

Views Tests – 3D Computer Model Group t-Test: Paired Two Sample for Means		
	View Pre-test	View 2
Mean	7.85	7.35
Variance	11.4	11.8
Observations	20	20
Hypothesized Mean Difference	0.00	
df	19.0	
t Stat	0.55	
P(T<=t) one-tail	0.29	
t Critical one-tail	1.73	
P(T<=t) two-tail	0.59	

The only category in which we can reliably compare the two groups of students is the one where there was a proven change in aptitude in both groups of the same test. That category is rotational reasoning aptitude.

TABLE 7
ROTATION TESTS

	Physical Model Group Rotations Difference	3D Computer Model Group Rotations Difference
Mean	0.80	-0.95
Variance	2.91	5.31
Observations	20	20
Pooled Variance	4.11	
Hypothesized Mean Difference	0.00	
df	38.00	
t Stat	2.73	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.69	

t-Test: Two-Sample Assuming Equal Variances

Qualitative Survey Results:

To ascertain the students' opinion on building a physical model or a computer model, both groups were asked 2 questions and asked to place their answers on a Likert scale of 1 (strongly disagree) to 5 (strongly agree):

1. The 3D model has helped me visualize 3D objects in different views:
The physical model group gave an average response of 4.05 = agree
The computer model group gave an average response of 3.5 = neither agree nor disagree

2. In my field, I believe that understanding what objects look like in different views will be of importance.
The physical model group gave an average response of 4.45 = agree
The computer model group gave an average response of 4.05 = agree

VI DISCUSSION

The only proven improvement in skills occurred in spatial visualization categories of rotations and views in the physical model group.

The data also showed that the physical model group had an improvement in the spatial visualization category of rotations that was statistically different from the degree of detriment in the same category of the computer group.

This study was focused on the pre and post-test spatial reasoning ability of both the physical model building students and the 3-D computer model building students. While the overall model project time of 8 weeks was the same for both groups, the time each group of students spent working on their models could not be accurately determined. The physical model building group did not spend any class time working on their models and they had other unrelated homework and quizzes that were also demanding of their time. The computer model groups were learning 3-D AutoCAD Architecture and Revit computer drafting programs and worked on their projects in class and outside of class as homework during the 8 week time period.

Other parameters which may have affected these results are the degree of preference or indifference each student had to their assigned model type, and their prior ability in their assigned model building type i.e. physical or computer drafted model.

Reasons for the detriment in the computer model building groups rotational spatial reasoning ability is undetermined.

With regard to the qualitative data, it is interesting to note that both groups of students agreed that understanding what objects look like in different views will be of importance in their field. Only the physical model group agreed that 3D models helped them visualize 3D objects in different views.

VII CONCLUSION

Integrating student-built physical models into freshmen courses improves student spatial visualization skill categories of rotations and views. Student-built computer models did not improve student spatial visualization skills in any of the 3 categories tested: developments, rotations and views. In fact, in this study, student-built computer models actually proved to be a statistically significant detriment to student visualization rotation skills when compared to the improvement in the same category seen in students who built physical models. This study has found that while faculty can depend on student-built physical models to improve student visualization rotational and views skills, student-built computer models cannot serve this role independently. In fact student-built computer models may be a detriment to student spatial visualization skills as shown in this study. More research is warranted, however, with a larger sample size. A literature review confirms that this is an area that would benefit from more research.

ACKNOWLEDGMENT

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REFERENCES

[1] Olkun, S. (2003) Making Connections: Improving Spatial Abilities with Engineering Drawing Activities. *International Journal of Mathematics Teaching and Learning*.

[2] National Science Board. (2010). Preparing the Next Generation of STEM Innovators: Identifying and Developing our Nation's Human Capital. Available at: http://www.nsf.gov/nsb/publications/2010/nsb1033.pdf

[3] Knapp, A. Why Schools Don't Value Spatial Reasoning. *Forbes*.December 27, 2011 accessed at http://www.forbes.com/sites/alexknapp/2011/12/27/why-dont-schools-value-spatial-reasoning/ on February 9,2014

[4] Humphreys, L. G., & Lubinski, D. (1996). Assessing spatial visualization: An underappreciated ability for many school and work settings. In C. P. Benbow & D. Lubinski (Eds.), *Intellectual talent: Psychometric and social issues*. Baltimore: Johns Hopkins University Press

[5] Agogino and Linn. (1992) Retaining Female Engineering

Students: Will Early Design Experience Help?, *NSF Directions*,. May-June National Science Foundation, p.8-9

[6] Haris et al –(2004)A Combination of Hand-Held Models and Computer Imaging Programs Help Students Answer Oral Questions about Molecular Structure and Function: A Controlled Investigation of Student Learning.

[7] Ming-Tang K, Jones L, Pulos S, Hyslop R. (2004) The Relationship of Molecular Representations, and Orientation to the Difficulty of Stereochemistry Problems *The Chemical Educator* v9 p1-7.

[8] Engage, Engaging Students in Engineering, retrieved from website: http://www.engageengineering.org/?page=4

[9] LoPiccolo, O., Implementing Student-Built Physical Models: Advanced Framing and 3" Cube to Improve Spatial Reasoning Ability Among Freshmen Architectural Engineering and Construction Management Students, ASEE National Conference 2011

[10]

[11] Fibonicci Spatial Reasoning Test, retrieved from website: http://www.fibonicci.com/spatial-reasoning/test/

[12] Purdue Spatial Visualization Test, retrieved from website: http://store.digitalriver.com/store/ets/DisplayProductDetailsPage/productID.39353200 accessed February 9, 2014