121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014

Paper ID #9262

Relationship Between Students' Spatial Visualization Ability and their Ability to Create 3D Constraint-Based Models from Various Types of Drawings

Dr. Theodore J. Branoff, North Carolina State University

Ted Branoff, Ph.D. is an associate professor in the department of STEM Education at North Carolina State University. He has been an ASEE member since 1987 and is the immediate past President of the International Society for Geometry and Graphics. Dr. Branoff's research interests include spatial visualization in undergraduate students, 3D constraint-based modeling strategies, and the effects of online instruction for preparing teachers and engineers. Along with teaching courses in introductory engineering graphics, computer-aided design, descriptive geometry, and instructional design, he has conducted CAD and geometric dimensioning & tolerancing workshops for both high school teachers and industry. In 2013 he was elected as an ASEE Fellow.

Prof. Modris Dobelis, Riga Technical University, Riga, Latvia

Dr.sc.ing., Professor, Head of Dep. of Computer Aided Engineering Graphics at the Riga Technical University. His research interests are Computer Aided Design in architecture, civil and mechanical engineering. He can be reached by e-mail: Modris.Dobelis@rtu.lv or through postal address: Dep. of Computer Aided Engineering Graphics, Riga Technical University, Azenes iela 16/20, LV-1048, Riga, Latvia.

Relationship Between Students’ Spatial Visualization Ability and their Ability to Create 3D Constraint-Based Models from Various Types of Drawings

Abstract

During the fall of 2013, a study was conducted where students completed the PSVT:R and the MCT and then were asked to complete three different modeling tasks. These tasks included modeling a part when given the object in the context of an assembly drawing, modeling a part when given an isometric pictorial of the object, and finally modeling a part when given a detail drawing of the object. Research questions for this study include the following: Does a simpler rubric provide similar scores as the previous rubric? Is there a relationship between a student’s spatial visualization ability and their ability to model a part from a pictorial, assembly drawing or detail drawing? Is the MCT still a better predictor of a student’s modeling success than the PSVT:R? Scores evaluated based on the simplified rubric were significantly higher than the scores evaluated based on the original rubric for the part modeled from the assembly drawing. This study revealed significant positive correlations between each modeling task and the two spatial visualization tests.

Review of Literature

Engineering graphics educators have been studying the computer-aided design modeling strategies of students for approximately 20 years. Studies involving constraint-based modeling have been more recent. These studies include students’ modeling strategies, conceptual framework research, and methods of evaluating models.

CAD Modeling Strategies

In a study of 34 technology education students, Chester found that strategic CAD instruction was more effective on novice CAD users than on CAD users with previously reported experience [8]. The experienced CAD users had formed strategies based on previously learned software that impeded their learning efficient strategies in the new software. He also makes some observations about research related to CAD [9]. Initial instruction and experience in the field does not necessarily lead to expertise. Experienced users still exhibit modeling strategies that are not optimal. Also, expertise is more about being able to apply strategic knowledge than just differentiating between command knowledge. True experts have knowledge of modeling strategies, and they know when to apply them appropriately. New CAD users tend to take very erratic approaches to modeling when they lack knowledge in design intent. Even when young students have a background in technical graphics and descriptive geometry, they have difficulty applying this knowledge to create CAD models with good design intent [11].

Conceptual Framework Research

Several conceptual framework models of CAD expertise have been developed over the last 15 years. Hartman developed a model of CAD expertise after studying practicing professionals in their native work environments [15-17]. He reports core themes, subordinate themes, and transitional themes demonstrated by experts. Core themes include strategy for tool use, problem definition and solution, design considerations, domain knowledge, and professional and academic experiences. The subordinate themes are software usage techniques, downstream uses of the CAD model, technical communication, social communication, requisite CAD model characteristics, and problem solving techniques. Finally, his transitional themes include the design environment, the way the expert worked, support structures, artifacts, personal characteristics, typical domain activities, conceptions of expertise, and factors related to CAD usage. Rynne & Gaughran [20] present a framework for parametric modeling and discuss attributes that experts demonstrate that are often missing from the models of novices. These attributes include the following: correct sketch plane selection for the base feature sketch; optimum model origin; correct base feature; correct part orientation; appropriate use of symmetry planes; simple sketch geometry; correct sketch relations; fully defined sketch geometry; correct feature sequence; parent-child feature relations; correct feature terminations; correct feature duplication; correct part design intent; and part accommodates planned and unforeseen design modification without feature failure. They further define the components of CAD expertise to include the general categories of the part modeling task, procedural 3D CAD knowledge, strategic 3D CAD knowledge, declarative 3D CAD knowledge, graphical and visualization capability, modeling deconstruction capability, and metacognitive processes [19].

Evaluating CAD Models

Studies involving the evaluation of CAD models have been quite diverse. In a study of the correlation between parametric modeling ability and performance on the Mental Cutting Test, Steinhauer used the general categories of approach, structure, accuracy, robustness, and creativity to assess students' models [21]. In a comparison of manual and online grading of solid models, Ault & Fraser evaluated models based on the following characteristics: correct geometry, appropriate choice and order of features, proper location of origin, proper view orientation, use diameter and radius dimensions correctly, correct hole placement, use of reference geometry for dependent features, and general modeling strategy [1]. Baxter and Guerci developed an automated grader for solid models. Their system allowed the instructor to determine exactly which constraint-based attributes were present in the student's file, but they do not offer a specific rubric to follow [2, 3]. More recently, studies have been conducted to examine students' ability to build specific design intent into models. Devine & Laingen outline a procedure used in their course that students can use to self-assess their models [12]. Students are given two self-check opportunities where they must measure a distance, one face area, and the total face area of the part. For the second self-check, students are required to change several dimensions on the part before measuring. This allows the instructor to determine if the initial dimensions captured the correct design intent. Peng et al. advocate for a similar approach [18]. Finally, Company, Contero & Salvado-Herranz summarize how they define the quality of a CAD model with the following five dimensions (p. 2) [10]:

1. Models are *valid* if they can be opened by suitable applications, and do not contain errors or warnings.
2. Models are *complete* if they include all product aspects relevant for design purposes.
3. *Consistent* models should not crash as a result of editing tasks or design exploration.
4. *Conciseness* pursuits models that do not include irrelevant information or procedures.
5. *Effective* CAD models convey design intent.

Engineering Graphics Literacy
A recent series of studies investigated students' ability to model parts when given assembly drawing information [4-7, 13]. These investigations revealed that the developed modeling test, as measured by the original rubric [6], had mixed results when examining relationships with measures in the course (e.g., final project and final exam). Some of these studies also examined whether students' modeling ability was related to their spatial visualization ability [4, 5, 7]. There were positive correlations between the PSVT:R and the modeling test (not all were significant) and significant positive correlations between the MCT and the modeling test. Recommendations included repeating the study using a shorter modeling activity, examining a more efficient way of evaluating the models, and using qualitative methods for evaluating modeling strategies.

Research Questions

The current study was designed to conduct a preliminary investigation into using an alternative rubric for assessing models. In addition, students were given alternative types of drawings (a pictorial and a detail drawing) to model, which were evaluated using the new rubric. To continue the theme of the previous engineering graphics literacy studies, correlations between the scores on the modeling activities and two standard visualization tests were also examined. The research questions for this study were:

1. Is there a difference in score between a model evaluated by the original rubric [6] and the same model evaluated by the new rubric?
2. Is there a relationship between a student's spatial visualization ability and their ability to model a part from an assembly drawing?
3. Is there a relationship between a student's spatial visualization ability and their ability to model a part from a pictorial drawing?
4. Is there a relationship between a student's spatial visualization ability and their ability to model a part from a detail drawing?
5. As with the previous studies, is the Mental Cutting Test a better predictor of a student's modeling ability than the Purdue Spatial Visualization Test:Visualization of Rotations?

Participants

In the Fall 2013 semester, 23 students enrolled in a junior-level constraint-based modeling course at North Carolina State University participated in the study. The course consists of engineering graphics standards and conventional practices (sectional views, dimensioning, threads & fasteners, and working drawings), geometric dimensioning and tolerancing, and constraint-based modeling techniques (assemblies, advanced drawing applications, macros, design tables, and rendering). Tables 1-3 summarize the demographic information of the participants.

Table 1. Gender of Participants.

Gender	Frequency	Percent
Female	3	13.04%
Male	20	86.96%
TOTAL	23	100.00%

Table 2. Academic Year of Participants.

Year	Frequency	Percent
Sophomore	3	13.04%
Junior	12	52.17%
Senior	8	34.78%
TOTAL	23	100.00%

Table 3. Academic Major of Participants.

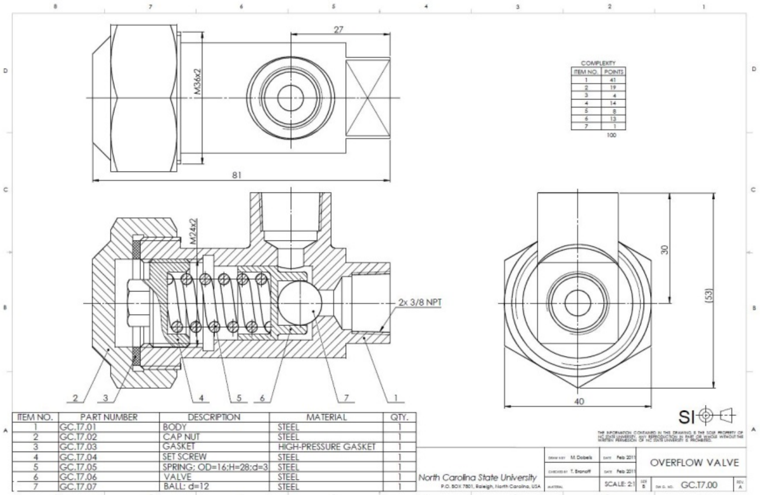
Major	Frequency	Percent
Agriculture & Environmental Science	2	8.70%
Civil Engineering	1	4.35%
Electrical Engineering	1	4.35%
Nuclear Engineering	1	4.35%
Mechanical and Aerospace Engineering	10	43.48%
Technology, Engineering & Design Education	8	34.78%
TOTAL	23	100.00%

Most of the students in the course were male from engineering or technology, engineering & design education. Technology, engineering & design education students take the course as part of their major requirements, while other students typically take the course as part of a 5 course minor in Graphic Communications.

The Modeling Activities

Previous studies related to the development of the engineering graphics literacy test used the modeling activity shown in Figure 1. In these previous studies, students were asked to model as many of the 7 parts in the assembly drawing as possible within a 110 minute class period. Some of the criticisms of this activity were that it took too long for students to complete and that it also took too long for instructors to evaluate. For the current study, students were only asked to model one of the parts in the given assembly – the SET SCREW (Figure 2). As with the previous studies, students were given a metric ruler and asked to scale dimensions directly off of the drawing. The assembly drawing was created with a drawing scale of 2:1. Only overall dimensions and a few other dimensions required for installation were given, including thread designations and sizes.

This study also examined students' ability to model parts when given a pictorial drawing and a detail drawing. The additional exercises used in the study are shown in Figures 3 & 4. The INDEX ARM [14] was selected because of its mixture of extrudes, cuts, holes, fillets, and symmetry. It has also been used in at least one other study at another institution, so some general comparisons might be made [21]. The RING was chosen for the detail drawing exercise because it is similar to existing parts in industry. It also requires students to be able to determine best strategies for using revolves and circular patterns.



COMPLEXITY

ITEM NO.	POINTS
1	41
2	19
3	4
4	14
5	8
6	13
7	1
	100

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	GC.T7.01	BODY	STEEL	1
2	GC.T7.02	CAP NUT	STEEL	1
3	GC.T7.03	GASKET	HIGH-PRESSURE GASKET	1
4	GC.T7.04	SET SCREW	STEEL	1
5	GC.T7.05	SPRING: OD=16;H=28;d=3	STEEL	1
6	GC.T7.06	VALVE	STEEL	1
7	GC.T7.07	BALL: d=12	STEEL	1

Figure 1. The Modeling Test Assembly Drawing.

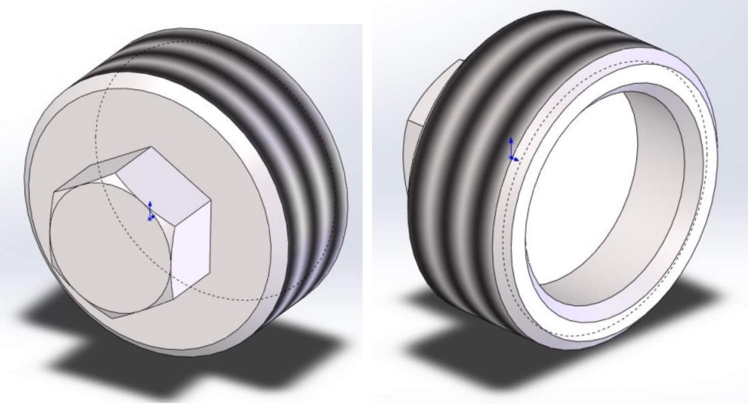


Figure 2. Completed Model of the SET SCREW.

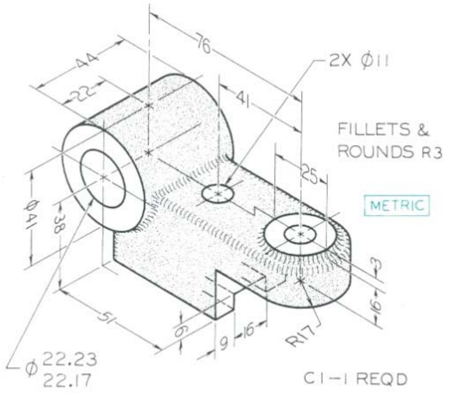


Figure 3. INDEX ARM [14].

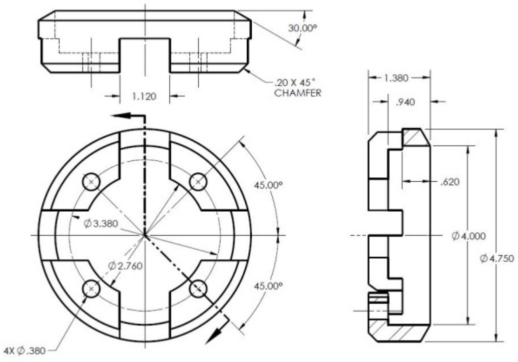


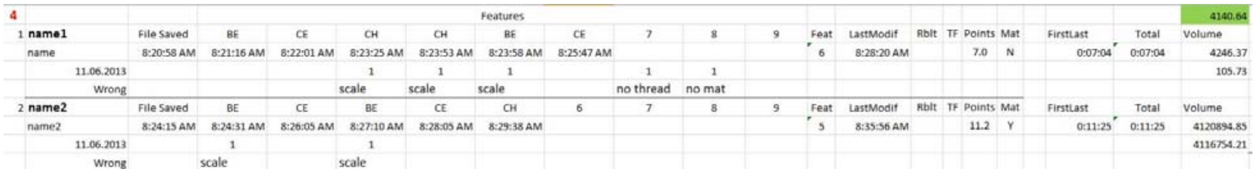
Figure 4. RING Drawing.

Methodology

The 18th class meeting of the semester was dedicated to a practical exercise in reading assembly drawings. Since both the practice modeling activity and the first modeling activity were metric and included some European standards, a 15 minute lecture was given on how to read SI drawings. Students were then shown strategies for modeling parts in the example problem. After the lecture, students were given the rest of class to model as many parts as possible in the practice drawing. During the 19th class meeting, students were administered an electronic version of the PSVT:R and the MCT within the Moodle learning management system. Each test was set up to terminate after 20 minutes. During the 21st class meeting, students were asked to model the SET SCREW, INDEX ARM, and RING. They were given 30 minutes to model each of the three parts.

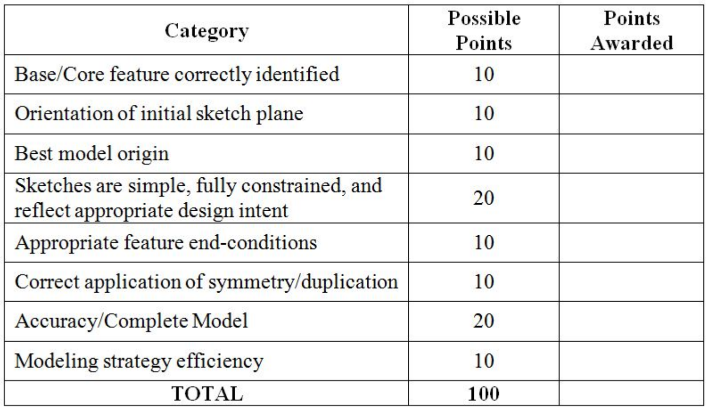
The Rubrics

The original assessment rubric spreadsheet [6] was created to account for model accuracy and time required to model each part (Figure 5). Each feature and sketch (if any) was analyzed individually. Penalty points were assigned for each wrong geometric dimension including under-defined sketches. Penalty points were added for each dimension of the geometric primitive missing in the model, incorrect dimensions, and failure to correctly represent cosmetic threads. The new rubric (Figure 6) was developed based on the review of literature and the themes that appeared throughout the different conceptual frameworks. Although some of the researchers applied point values to each category in their rubrics, there was no consistency in the weighting of the categories. For the current study, weights were given on the basis of the relevant importance of each category to the problem solution.



4							Features														4140.64
1	**name1**	File Saved	BE	CE	CH	CH	BE	CE	7	8	9	Feat	LastModif	Rblt	TF	Points	Mat		FirstLast	Total	Volume
	name	8:20:58 AM	8:21:16 AM	8:22:01 AM	8:23:25 AM	8:23:53 AM	8:23:58 AM	8:25:47 AM				6	8:28:20 AM			7.0	N		0:07:04	0:07:04	4246.37
	11.06.2013				1	1	1		1	1											105.73
	Wrong				scale	scale	scale		no thread	no mat											
2	**name2**	File Saved	BE	CE	BE	CE	CH	6	7	8	9	Feat	LastModif	Rblt	TF	Points	Mat		FirstLast	Total	Volume
	name2	8:24:15 AM	8:24:31 AM	8:26:05 AM	8:27:10 AM	8:28:05 AM	8:29:38 AM					5	8:35:56 AM			11.2	Y		0:11:25	0:11:25	4120894.85
	11.06.2013		1		1																4116754.21
	Wrong		scale		scale																

Figure 5. Original Rubric [6].



Category	Possible Points	Points Awarded
Base/Core feature correctly identified	10	
Orientation of initial sketch plane	10	
Best model origin	10	
Sketches are simple, fully constrained, and reflect appropriate design intent	20	
Appropriate feature end-conditions	10	
Correct application of symmetry/duplication	10	
Accuracy/Complete Model	20	
Modeling strategy efficiency	10	
TOTAL	100	

Figure 6. New Rubric.

When the modeling activities were complete, the researcher evaluated the models in the following order and with the identified rubrics:

1. All SET SCREW models were evaluated with the original rubric.
2. All SET SCREW models were evaluated with the new rubric.
3. All INDEX ARM models were evaluated with the new rubric.
4. All RING models were evaluated with the new rubric.

Analysis of Results

Table 4 displays the descriptive statistics for the study. All students completed the two visualization tests and made some attempt at the SET SCREW, and the RING. One student did not complete any part of the INDEX ARM.

Table 4. Descriptive Statistics.

	N	Min.	Max.	Mean	Std. Dev.	Variance
SET SCREW – Original Rubric	23	20.00	90.00	64.78	21.45	460.18
SET SCREW – New Rubric	23	65.00	95.00	83.87	6.99	48.85
INDEX ARM – New Rubric	23	0.00	100.00	80.43	19.31	372.71
RING – New Rubric	23	46.00	98.00	77.43	14.41	207.71
PSVT:R	23	10.00	30.00	25.39	5.26	27.70
MCT	23	8.00	24.00	17.65	4.73	22.33

Research Question 1: Is there a difference in score between a model evaluated by the original rubric [6] and the same model evaluated by the new rubric? Figure 7 displays the scores for each student's SET SCREW model when evaluated using each of the rubrics. The graph reveals a large disparity in scores for models that tended to be low in quality. The two rubrics seem to be a little more consistent for models that are closer to being correct. To evaluate this research question, a paired sample t-test was used. Table 5 displays the results for this test.

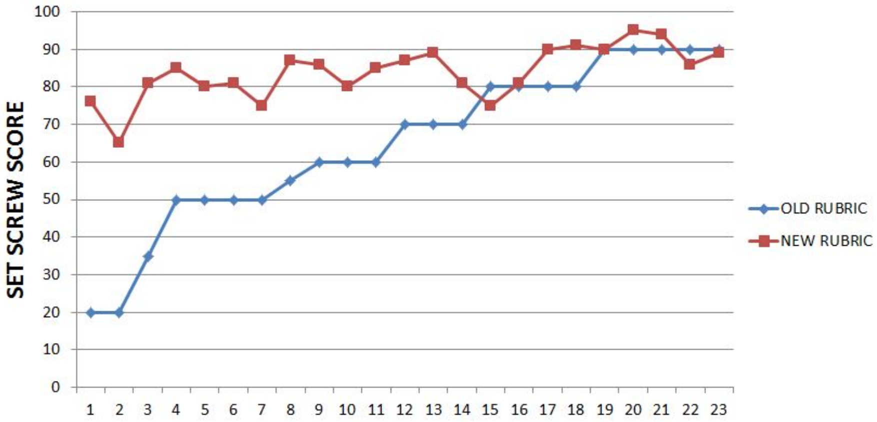


Figure 7. Scores using the Original Rubric vs. New Rubric on the SET SCREW.

Table 5. Paired Sample t-test.

	Paired Differences			t	df	Sig. (2-tailed)
	Mean	Std. Dev.	Std. Error Mean			
Pair 1	-19.087	17.069	3.559	-5.363	22	.000

There was a significant difference between the SET SCREW scores evaluated based on the original rubric and the SET SCREW scores evaluated based on the new rubric. Examination of the mean scores shows that using the new rubric tended to result in higher scores.

Research Questions 2-4: Is there a relationship between a student's spatial visualization ability and their ability to model a part from an assembly drawing, pictorial drawing, or detail drawing?
Research Question 5: Is the Mental Cutting Test a better predictor of a student's modeling ability than the Purdue Spatial Visualization Test:Visualization of Rotations?

The data was examined to see if there were identifiable differences in the means between the scores on the modeling tests and the scores on the PSVT:R, and MCT. Also of interest was the relationship between the PSVT:R and MCT. Figures 5-13 display scatterplots for these data to provide a visual representation.

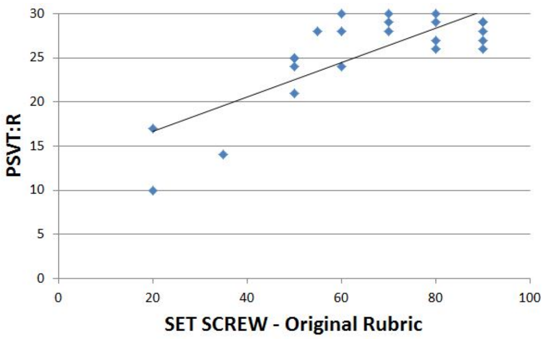


Figure 5. SET SCREW – Original Rubric vs. PSVT:R.

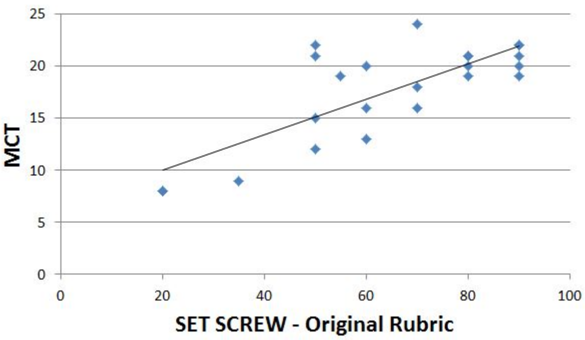


Figure 6. SET SCREW – Original Rubric vs. MCT.

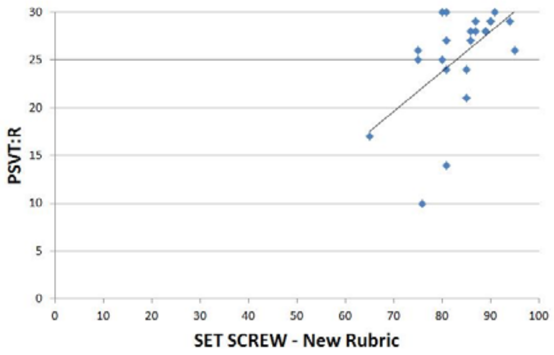


Figure 7. SET SCREW – New Rubric vs. PSVT:R.

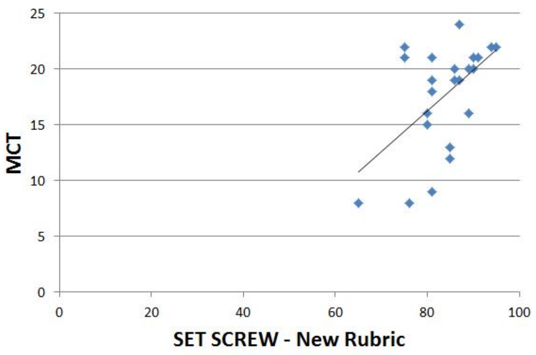


Figure 8. SET SCREW – New Rubric vs. MCT.

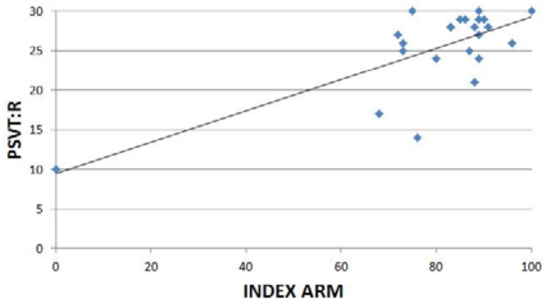


Figure 9. INDEX ARM vs. PSVT:R.

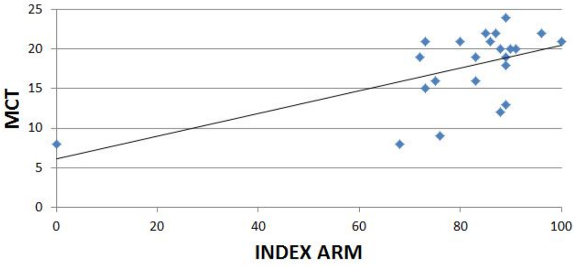


Figure 10. INDEX ARM vs. MCT.

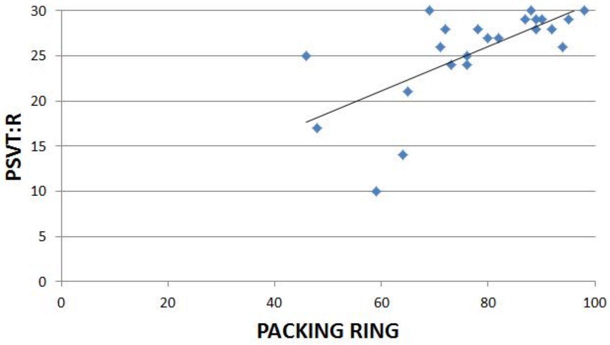


Figure 11. RING vs. PSVT:R.

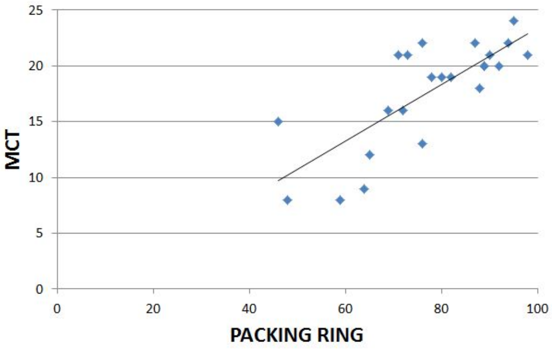


Figure 12. RING vs. MCT.

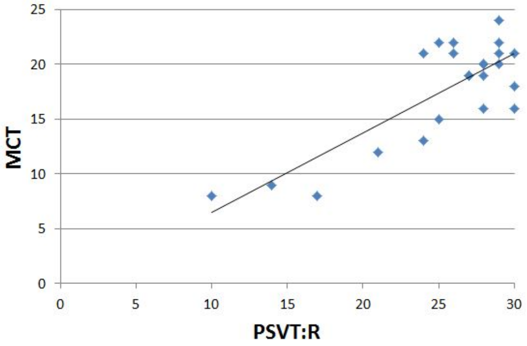


Figure 13. PSVT:R vs. MCT.

The scatterplots for the data display a positive relationship between the scores on the modeling activities and the scores on the PSVT:R and MCT. The descriptive statistics for the data show that the some of the modeling scores were very spread out with large standard deviations. To get a better feel for the shape of the data for these variables, histograms are displayed in Figures 14-19.

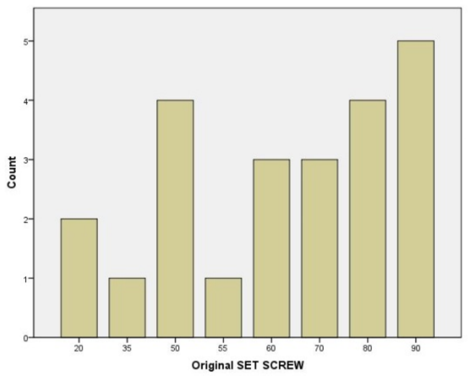


Figure 14. SET SCREW – Original Rubric.

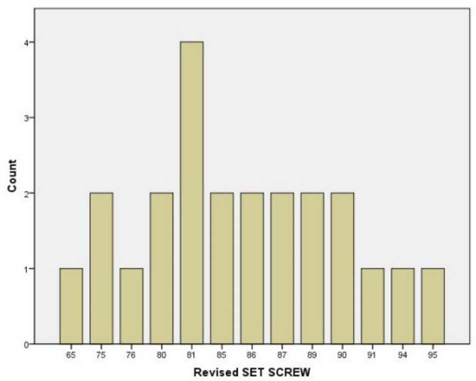


Figure 15. SET SCREW – Revised Rubric.

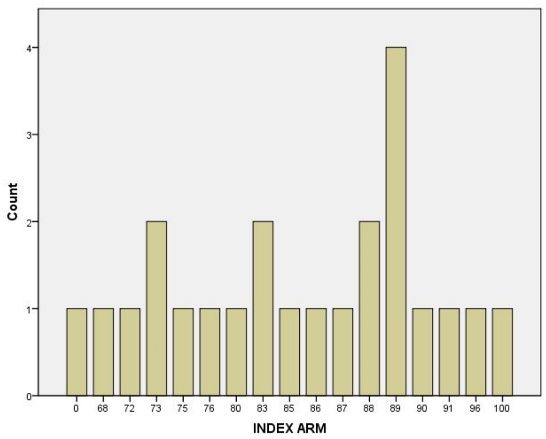


Figure 16. INDEX ARM Histogram.

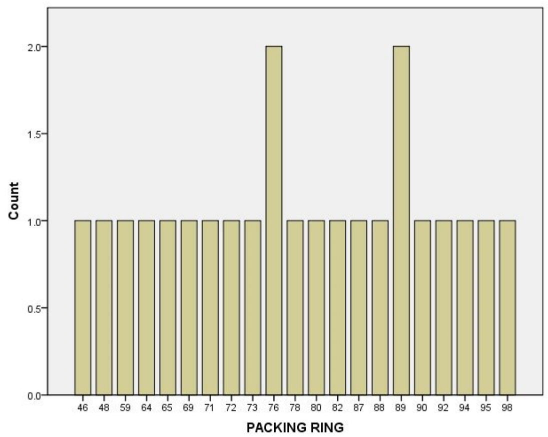


Figure 17. RING Histogram.

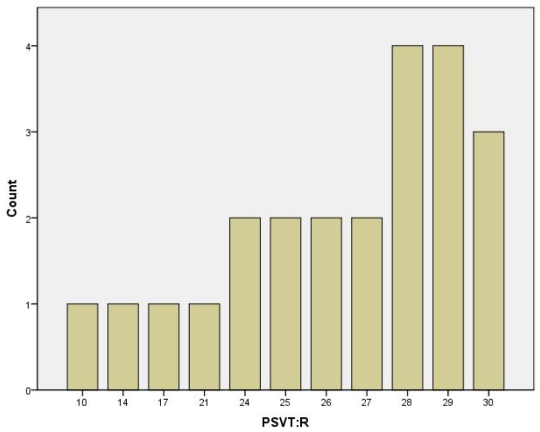


Figure 18. PSVT:R Histogram.

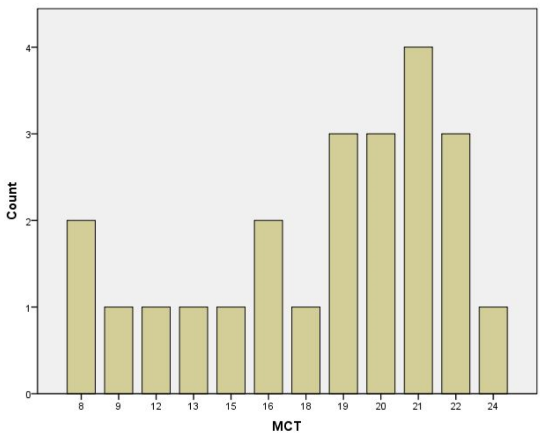


Figure 19. MCT Histogram.

The distributions of the data do not appear to be normal, therefore, they do not meet the assumptions for parametric tests. A non-parametric Spearman's Rho was used to test research questions 2-5. Table 6 displays the data for these analyses.

Table 6. Spearman's Rho Correlations.

Spearman's rho		SET SCREW Original Rubric	SET SCREW New Rubric	INDEX ARM	RING	PSVT:R	MCT
SET SCREW Original Rubric	Correlation Coefficient	1.000					
	Sig. (2-tailed)	.					
	N	23					
SET SCREW New Rubric	Correlation Coefficient	.574**	1.000				
	Sig. (2-tailed)	.000	.				
	N	23	23				
INDEX ARM	Correlation Coefficient	.376*	.525**	1.000			
	Sig. (2-tailed)	.018	.001	.			
	N	23	23	23			
RING	Correlation Coefficient	.582**	.570**	.614**	1.000		
	Sig. (2-tailed)	.000	.000	.000	.		
	N	23	23	23	23		
PSVT:R	Correlation Coefficient	.485**	.426**	.343*	.528**	1.000	
	Sig. (2-tailed)	.003	.007	.028	.001	.	
	N	23	23	23	34	23	
MCT	Correlation Coefficient	.513**	.416**	.363*	.596**	.379*	1.000
	Sig. (2-tailed)	.001	.008	.020	.000	.017	.
	N	23	23	23	34	34	23

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The Spearman's Rho analyses show significant positive correlations between scores on all of the modeling activities and both visualization tests. As one might expect, there was also a significant positive correlation between the PSVT:R and the MCT ($\rho = .379$, $\alpha = .017$).

Discussion and Conclusions

The analyses revealed that there was a significant difference in scores on the SET SCREW when the parts were evaluated with two different rubrics by this researcher. Scores were significantly higher when evaluated with the new rubric. The original rubric tended to penalize students more for making errors within each feature, which resulted in much lower scores. This may be a more useful assessment of models within the context of industry. Models that are not valid and do not behave with correct design intent will cause problems in a production environment. Whether a model was rated as a 50 with the original rubric or as an 85 with the new rubric may not matter.

This model will still not be useful in practice. The time required to correct the model might be another important issue to examine. Educators should strive for instructional methods that help students understand appropriate design intent for a specific situation by giving students an opportunity to change the parameters within a model. Some of these instructional practices are already outlined in previous research [12, 18, 22].

The Spearman Rho analyses of the data revealed that there are significant correlation between students' scores on the modeling activities and the two spatial visualization tests. In this study students who scored higher on the PSVT:R and MCT tended to score higher on the modeling activities. In general, the MCT had a higher correlation value with the modeling activities than the PSVT:R. This is consistent with the previous research [5]. Clearly there are factors other than spatial visualization that are involved in students' ability to model parts from detail drawings, assembly drawings, and pictorial drawings (e.g., problem definition and solution, design considerations, domain knowledge, and professional and academic experiences, strategic CAD knowledge, procedural CAD knowledge, etc.). Spatial visualization ability does appear to play a key role.

Future Research

There are still questions that need to be answered regarding constraint-based modeling strategies and how models are evaluated. In this study and previous studies [4-7], one researcher evaluated all of the models. A recommendation is to examine the inter-rater reliability of the rubrics used in this study. Having multiple persons evaluate each model using one rubric will give a better picture of the validity and reliability of these evaluation methods. Another recommendation is to examine the modeling strategies of students using qualitative methods. Although some of the students in this study created models that were the correct volume, their modeling strategies did not exhibit good design intent. Other students struggled to even begin the modeling activity. Qualitative techniques may shed more light on what students were thinking about when they created their models.

References

1. Ault, H. K., & Fraser, A. (June, 2013). A comparison of manual vs. online grading for solid models. *Proceedings of the 2013 ASEE Annual Conference, Atlanta, Georgia, June 23-26, 2013.*
2. Baxter, D.H. (2003). Evaluating an automatic grading system for an introductory computer aided design course. *Proceedings of the 58th Annual Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education, Scottsdale, Arizona, November 16-19, 2003.*
3. Baxter, D.H. & Guerci, M. J. (2003). Automating an introductory computer aided design course to improve student evaluation. *Proceedings of the 2003 Annual Conference of the American Society for Engineering Education, Nashville, Tennessee, June 22-25, 2003.*
4. Branoff, T. J., & Dobelis, M. (October, 2013). Spatial visualization ability and students' ability to model objects from engineering assembly drawings. *Paper published in the proceedings of the 68th Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education, Worcester, Massachusetts, October 20-22, 2013.*
5. Branoff, T. J., & Dobelis, M. (June, 2013). The relationship between students' ability to model objects from assembly drawing information and spatial visualization ability as measured by the PSVT:R and MCT.

Proceedings of the 2013 Annual Meeting of the American Society for Engineering Education, Atlanta, Georgia, June 23-26, 2013.

6. Branoff, T. J., & Dobelis, M. (January, 2012). Engineering graphics literacy: Measuring students' ability to model objects from assembly drawing information. *Paper published in the proceedings of the 66th Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education, Galveston, Texas, January 22-24, 2012.*
7. Branoff, T. J., Dobelis, M. (2012). The relationship between spatial visualization ability and students' ability to model 3D objects from engineering assembly drawings. *Engineering Design Graphics Journal*, 76 (3), 37-43.
8. Chester, I. (2007). Teaching for CAD expertise. *International Journal of Technology and Design Education, 17,* 23-35.
9. Chester, I. (2008). 3D-CAD: Modern technology – outdated pedagogy? *Design and Technology Education: An International Journal, 12(1),* 7-9.
10. Company, P., Contero, M., & Salvador-Herranz. (July, 2013). Testing rubrics for assessment of quality in CAD modelling. *Proceedings of the Research in Engineering Education Symposium, Kuala Lumpur, Malaysia, July 4-6, 2013.*
11. Delahunty, T., Seery, N., & Lynch, R. (2012). An evaluation of the assessment of graphical education at junior cycle in the Irish system. *Design and Technology Education: An International Journal, 17(2),* 9-20.
12. Devine, K. D., & Laingen, M. A. (October, 2013). Assessing design intent in an introductory-level engineering graphics course. *Paper published in the proceedings of the 68th Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education, Worcester, Massachusetts, October 20-22, 2013.*
13. Dobelis, M., Branoff, T., Nulle, I. Assessment of the Engineering Graphic Literacy Skills. In: *Engineering Graphics BALTGRAF 2013: Scientific Proceedings of the 12th International Conference on Engineering Graphics: The 12th International Conference on Engineering Graphics BALTGRAF 2013*, Latvia, Rīga, 5-7 June, 2013. Riga: Riga Technical University, 2013, pp.69-80. ISBN 9789934507304.
14. Giesecke, F. E., Mitchell, A., Spencer, H. H., Hill, I. L., Loving, R. O., Dygdon, J. T., & Novak, J. E. (2000). *Engineering Graphics*. 8th Edition. Upper Saddle River, New Jersey: Pearson, Prentice Hall.
15. Hartman, N. W. (2003). *Towards the definition and development of expertise in the use of constraint-based CAD tools: Examining practicing professionals* (Unpublished doctoral dissertation). North Carolina State University, Raleigh, North Carolina.
16. Hartman, N. W. (2009). The development of expertise in the use of constraint-based CAD tools: Examining practicing professionals. *Engineering Design Graphics Journal, 68(2),* 14-26.
17. Hartman, N. W. (2009). Defining expertise in the use of constraint-based CAD tools by examining practicing professionals. *Engineering Design Graphics Journal, 69(1),* 6-15.
18. Peng, X., McGary, P., Johnson, M., Yalvac, B., & Ozturk, E. (2012). Assessing novice CAD model creation and alteration. *Computer-Aided Design & Applications, PACE, (2),* 9-19.
19. Rynne, A., Gaughran, W. F., & Seery, N. (2010). Defining the variables that contribute to developing 3D CAD modelling expertise. In E. Norman & N. Seery (Eds.), *Graphicacy and Modelling*. The International Conference on Design and Technology Educational Research and Curriculum Development, Loughborough, U.K. 161-233.
20. Rynne, A., & Gaughran, W. (June, 2007). Cognitive modelling strategies for optimum design intent in parametric modelling (PM). *Proceedings of the 2007 Annual Meeting of the American Society for Engineering Education,Honolulu, Hawaii, June 24-27, 2007.*
21. Steinhauer, H. M. (2012). Correlation between a student's performance on the Mental Cutting Test and their 3D parametric modeling ability. *Engineering Design Graphics Journal, 76(3),* 44-48.
22. Wiebe, E. N., Branoff, T. J., & Hartman, N. W. (2003). Teaching geometry through dynamic modeling in introductory engineering graphics. *Engineering Design Graphics Journal*, 67 (2), 12-20.