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

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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. 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. 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.

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. 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 pursues 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>
<thead>
<tr>
<th>Gender</th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>3</td>
<td>13.04%</td>
</tr>
<tr>
<td>Male</td>
<td>20</td>
<td>86.96%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>23</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
Table 2. Academic Year of Participants.

<table>
<thead>
<tr>
<th>Year</th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sophomore</td>
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<td>13.04%</td>
</tr>
<tr>
<td>Junior</td>
<td>12</td>
<td>52.17%</td>
</tr>
<tr>
<td>Senior</td>
<td>8</td>
<td>34.78%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>23</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 3. Academic Major of Participants.

<table>
<thead>
<tr>
<th>Major</th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture &amp; Environmental Science</td>
<td>2</td>
<td>8.70%</td>
</tr>
<tr>
<td>Civil Engineering</td>
<td>1</td>
<td>4.35%</td>
</tr>
<tr>
<td>Electrical Engineering</td>
<td>1</td>
<td>4.35%</td>
</tr>
<tr>
<td>Nuclear Engineering</td>
<td>1</td>
<td>4.35%</td>
</tr>
<tr>
<td>Mechanical and Aerospace Engineering</td>
<td>10</td>
<td>43.48%</td>
</tr>
<tr>
<td>Technology, Engineering &amp; Design Education</td>
<td>8</td>
<td>34.78%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>23</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

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.
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 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 undefined 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.

![Figure 5. Original Rubric](image)

![Figure 6. New Rubric](image)
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>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Dev</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SET SCREW – Original Rubric</td>
<td>23</td>
<td>20.00</td>
<td>90.00</td>
<td>64.78</td>
<td>21.45</td>
<td>460.18</td>
</tr>
<tr>
<td>SET SCREW – New Rubric</td>
<td>23</td>
<td>65.00</td>
<td>95.00</td>
<td>83.87</td>
<td>6.99</td>
<td>48.85</td>
</tr>
<tr>
<td>INDEX ARM – New Rubric</td>
<td>23</td>
<td>0.00</td>
<td>100.00</td>
<td>80.43</td>
<td>19.31</td>
<td>372.71</td>
</tr>
<tr>
<td>RING – New Rubric</td>
<td>23</td>
<td>46.00</td>
<td>98.00</td>
<td>77.43</td>
<td>14.41</td>
<td>207.71</td>
</tr>
<tr>
<td>PSVT:R</td>
<td>23</td>
<td>10.00</td>
<td>30.00</td>
<td>25.39</td>
<td>5.26</td>
<td>27.70</td>
</tr>
<tr>
<td>MCT</td>
<td>23</td>
<td>8.00</td>
<td>24.00</td>
<td>17.65</td>
<td>4.73</td>
<td>22.33</td>
</tr>
</tbody>
</table>

Research Question 1: Is there a difference in score between a model evaluated by the original rubric 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.](image)
Table 5. Paired Sample t-test.

<table>
<thead>
<tr>
<th>Paired Differences</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error Mean</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>-19.087</td>
<td>17.069</td>
<td>3.559</td>
<td>-5.363</td>
<td>22</td>
<td>.000</td>
</tr>
</tbody>
</table>

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](image1.png)

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

![Figure 6](image2.png)

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

![Figure 7](image3.png)

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

![Figure 8](image4.png)

Figure 8. SET SCREW – New Rubric 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.
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.
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**


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.


