Improvements in Student Spatial Visualization in an Introductory Engineering Graphics Course using Open-ended Design Projects Supported by 3-D Printed Manipulatives

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Improvements in student Spatial Visualization in an introductory engineering graphics course using open-ended design projects supported by 3D printed manipulatives

Abstract
This work-in-progress reports changes in development of Spatial Visualization (SV) skills in students taking a first semester Engineering Design Graphics course modified to integrate geometric design modules supported by manipulative production through 3D printing.

The ability to imagine three dimensional objects, to visualize them in rotated states, and to subsequently communicate them in 2D (sketches) and 3D space (virtual solid models) is a critical skill for engineers, and a large body of research has shown that the development of these skills is indicative of student success and persistence in engineering. Thus a course that due to its non-mathematical nature is often perceived as non-critical, in practice has demonstrated to be of high importance, as it is where decisions for exiting the program are made.

The improvement of the development of SV skills during the freshman year has also received significant attention in the literature. The widespread teaching of 3D solid modeling software for the past two decades has introduced the capability to easily visualize objects in three dimensions, and typically constitutes the core content of the first design course. The flipside of this development is that the learning curve for the normally employed parametric solid modeling software is steep, and requires explicit instruction on the use of the software. Thus the course often has a focus on learning the software (which is typically done by requiring the students to learn the software by modeling existing 2D or 3D representations of an object), and not a design focus, where students develop a geometric solution to a stated problem without having any prior representation of the solution. The latter clearly requires the students to visualize the geometry of a solution before it is generated (either on paper or virtually in the computer).

The work in progress presented here assesses differences in SV development in students enrolled in two sections of the same Engineering Graphics and Design course during the Fall 2015 semester; one that is taught in the traditional fashion and that represents a control group of 80 students, and a second section (76 students) modified to include two week-long and appropriately scaffolded geometric design exercises. Part visualization is supported by requiring the students to use and/or print 3D manipulatives of the parts that constitute the connecting elements to their freeform design problem, and to generate prototypes of their final solution in order to test assembly capability. The assessment tool utilized is the Purdue Spatial Visualization Test Rotations, administered in pre and post mode in both sections.

Introduction
The ability to process visual information and the ability to create mental images of two-dimensional representations of existing objects are critical skills for engineering
students, as solutions to analytical engineering problems as well as the ideation process in design require spatial visualization (SV) skills. All sighted individuals have the ability to process visual information; however, not everyone can inherently process visual information at the same level or speed\(^1\). Cognitive training is required not only to process visual information faster but also to enhance SV ability\(^2\).

Based on differing levels of innate ability, prior training and experience, engineering students enter the first semester with greatly varying levels of SV aptitude, with many first-year engineering students not having developed the visual analysis and synthesis skills needed in engineering (visual analysis is the ability to see objects and express them through graphical representations, while visual synthesis is the ability to imagine or create a mental image of an object and express them through graphical representations). This problem has been widely reported and addressed in prior work\(^2–7\), and numerous strategies have been explored. The advent of 3D solid modeling over the past three decades has supported this development by introducing an easy way to virtually visualize objects in three dimensions. As a result, industry and engineering programs have embraced this technology, and now learning an industry-typical CAD software package typically represents the backbone of the first design course. The flipside of this development is that the learning curve for modern parametric solid modeling software is steep, and requires explicit instruction on the use of the software. Thus typical first-year Engineering Design Graphics courses typically focus on teaching a specific CAD software package, and do not specifically address the development of students SV skills and self-regulation, which are direct indicators of student academic success and persistence in STEM\(^8,9\).

The research presented here specifically targets the development of SV skills by designing and implementing geometric design modules supported by the creation and use of 3D manipulatives.

**Spatial visualization: Synopsis of literature**

The importance of SV has received much attention over the past years. Already in 1955, the Grinter Report\(^10\) outlined a vision of engineering education that clearly addresses the necessity of developing SV skills, this report was followed by numerous studies have reiterated the importance of SV skills and their link to success in the technical disciplines.

The assessment of SV skills builds primarily on the seminal work of Shepard and Meltzer\(^11\) that has resulted in the Mental rotations Test (MRT), and Guay’s Purdue Spatial visualization Test Rotations (PSVT:R)\(^12\). Their work has created the foundation of a range of tests that have been developed over the past decades\(^4\). Typically SV tests rely on students interpreting the graphical representation of 3D objects, and identifying which of the graphical representations given corresponds to the reoriented object. The PSVT:R used here introduces rotations about one, two and three axes, which are presented in increasingly difficult increments. Students need to identify the correct rotated representation in a multiple-choice environment within a limited time window. Not only is SV an important skill for engineers, but it is also linked to academic success. Recent studies, such as the one conducted by Lubinski in 2010\(^8\), relate success and persistence in the STEM fields to high levels in SV at the adolescent age:
“...the consistently distinguished levels of spatial ability among adolescents who subsequently go onto earn STEM educational degrees and occupations, relative to adolescents who secure educational credentials and occupations in other areas, reveals the importance of spatial ability in STEM arenas.” (Lubinski, 2010)

A number of secondary and tertiary level studies 3, 9, 2, 5, 13 clearly ratify this development by observing the SV development in first-year engineering students. Moreover, this clear research based link between high SV skills and academic success has also unveiled a gender gap, showing a widely reported male advantage over females in the results of the SV tests 14, 15, 16, 17, 18, 12. This male advantage can have detrimental effects:

“Design Graphics courses are among the first courses in which first-year engineering students enroll. For this reason, students who have poorly developed spatial skills, particularly women, may become discouraged and drop out of engineering altogether if they are struggling in their first engineering course while their classmates seemingly breeze through the material.” (Sorby, 2009 3)

It is critical to address SV skills early in the professional formation of engineers to not only ensure adequate technical skill acquisition, but also to address this gender gap in order to support increased female persistence in engineering programs.

Sorby 2, 3, 5, 19 has investigated and implemented a number of interventions to help students overcome SV deficiencies by proposing increased hand-sketching, creating shapes from paper cutouts, as well as having online visualization modules. Results indicate improvements in SV for students that undergo these remedial measures. Sorby concludes that courses that “stressed hands-on sketching and drawing tended to improve spatial skills more than those courses that stress computer aided design methods” 20. In contrast, Connolly et al 21 report that the remedial SV modules (workbook and CD, but no physical manipulatives) developed and applied in the context of a multi-institution collaboration show no statistically significant improvement.

To date, explicitly addressing the development of SV skills in first-year engineering students has been focused on these activities that favor students’ creative graphical expression over focused software learning. With regard to manipulatives and gestures supporting the development of SV skills, significant work has been done Chu and Kita 22, 25, who have addressed the beneficial aspects of gestures in spatial problem solving, and investigated changes that occur over time as the subjects develop proficiency in SV. Their results show that while the gesture and manipulation motor strategy becomes increasingly internal and decoupled from the physical agent as proficiency increases 22, the use of a motor strategy does indeed support the development of SV 23. Study 24 carried out an extensive analysis on the relationship between and assessment of haptic and visual abilities in freshman engineering students, concluding that there are indications that visual and haptic abilities are not mutually exclusive.

Three-dimensional manipulatives have been used in instruction in a number of disciplines to support the visualization of objects, such as anatomy 25, to quickly produce
adequate wind tunnel testing models in aeronautical engineering, and as learning tools in undergraduate Mechanics courses. In addition, manipulatives have received attention in secondary education, both in teacher and student education. However, there has been little systematic use of 3D printed manipulatives to enhance SV in early engineering graphics courses. Roberts and Chevrier investigated the effect of changing from 2D representations to 3D manipulatives on the SV response of men and women. They discovered that the introduction and manipulation of physical objects enhances the development of SV for all participants, albeit without altering the male’s speed advantage in the solution of SV assessments. Czapka et al. introduced 3D printed manipulatives into an engineering design graphics course. The manipulatives were pre-produced and used to provide students with a haptic orientation with a channel for enhanced learning, and results obtained ratify the effectiveness of the intervention.

The work in progress research presented here extends this work by combining the introduction of manipulatives with geometric design projects that require students to mentally visualize a design, and not simply recreate it from an existing representation.

Method

Approach

This research compares changes in student SV between two sections of the same engineering design graphics freshman course (MEE120, at the University of Maine) during the fall 2015 semester; one section following the traditional approach and acting as control group (section “CG”), and another section (section “GD”, for “Geometric Design”) that introduces a sequence of geometric design projects and 3D printing activities.

The relatively new 2 credit hour MEE120 course (first developed and taught in 2014) meets once a week for 3 hours. The lectures and labs are conducted by the instructor with the help of an undergraduate student, and typically consist of short lectures followed by tutorials and exercises. The course’s learning outcomes were maintained equal for both sections of the course.

The introduction of the geometric design modules does not reduce the material covered in traditional format. All learning outcomes are completed for both approaches.

Design

In order to assess differences (attributable to the different pedagogic elements of manipulatives and geometric design) in the improvement of SV skills between the GD section and the control group, these changes need to be quantified and compared. The normal assessment of the course targets the attainment of the learning outcomes, which do not explicitly reflect SV skills, and can thus not be used to quantify improvements in SV. A further challenge is the difference in the order of topic presentation that the two experienced instructors favor, thereby inhibiting the development and use of a formative assessment method to quantify the impact of the individual pedagogic measures on the students SV skill development.

There are a number of tools that have been developed to assess SV development, with perhaps the most widely used (in the US) being the Purdue Spatial Visualization
Test (PSVT \(^{34}\)), of which often only the rotations section is used (PSVT:R) \(^{35}\). Sorby and Gorska \(^{4}\) and Study \(^{24}\) present a comparative of a number of available tests, such as the Mental Rotations Test (MRT) \(^{36}\), the Mental Cutting Test (MCT, 1939), the Differential Aptitude Test: Space Relations (DAT:SR).

For this study, and in order to assess changes in spatial visualization consistently across both sections of the course, the Purdue Spatial Visualization Test Rotations (PSVT:R, \(^{34}\)) was chosen, and administered in pre and post mode to both sections of the course. An electronic version of the PSVT:R was created and administered through the course management system, in order to ensure consistent administration.

The test consists of 30 questions that require the user to mentally rotate unknown geometric objects in a sequence of increasing difficulty \(^{34}\). The pre-test was administered during the first class period, before any instruction took place. The post-test was administered during the last week of classes.

The PSVT:R has been one of the standard assessment instruments for SV over the past 30 years, having undergone a number of validations that indicate that the scores are reliable for measuring SV ability for first year engineering students \(^{37, 38, 21, 33}\), and thus was deemed suitable to assess differences in SV between the two sections tested here. A further benefit is as it allows continuous compilation of data and comparison with previously administered assessments \(^{39}\) at the University of Maine and beyond \(^{12, 37, 35, 40}\).

**Participants**

The class enrollment for the CG and GD sections was 80 and 76 respectively, of which 60 and 52 students respectively participated in the PSVT:R assessment as a matched pair. The demographics are typical a first semester Mechanical Engineering course, with predominantly traditional students (however no specific data on traditional vs. non-traditional was collected), and 8% female participation, which is aligned with the department average of 9%.

**Implementation**

**The existing approach – the Control Group section**

The traditional course instruction begins with two to three weeks introducing engineering graphics with hand sketching in Isometric and Orthographic projections, followed by four to five weeks discussing several topics covering engineering drawings and standards (e.g. views, dimensioning, fits and tolerances, and threading). The introduction of the CAD package occurs early in the semester, and is concurrent to related hand-sketching and engineering drawing topics of the course. Sequence of the CAD package’s components begins with constraint-based sketching, followed by part development, production of engineering drawings, and finally part assemblies. All these CAD components are taught in the context of a specific CAD package (such as SolidWorks or CREO), and follow a software-specific text.

Instruction time of the CAD package consists of “learning-the-tool” demonstrations, followed by students completing a sequence of tutorials and exercises from the text. The text guides the students through these activities, where they learn to reproduce given sketches, parts and assemblies. The components to be modeled are
given in a representation that the students already know; typically 2D orthographic engineering drawings are given to be built as solid models. These exercises and tutorials, which span approximately two thirds of the semester, do not require the student to imagine a geometric solution, but rather only to interpret a given 2D representation.

Homework assignments also follow this approach, as students are tasked with building a radial engine’s 16 unique components as solid models, but again originating from the familiar 2D orthographic engineering drawings. Students are also required to create proper engineering drawings using the CAD package, since the assigned drawings are often intentionally faulty according to conventional drawing standards.

![Semester project for control group section](image)

Figure 1. Semester project for control group section

Components are assigned so that they, and/or the resulting engineering drawings, reinforce recently taught concepts. In the same manner, the topic of assembly modeling occurs when the radial engine’s components are ready to be assembled (Figure 1).

**The modified approach: the geometric design section**

While initial familiarization with the modeling environment and feature creation continues to be based on modeling exercises and tutorials, the geometric design modules introduce a step change in the software use. In contrast to the traditional modeling mode, where the students’ principal challenge is using the software to create the given model, in geometric design mode the students’ main challenge is to devise a non-existing solution to a geometric design problem. The students are required to use all forms of graphical representation studied (including hand sketching for initial concepts), and are required to apply the engineering design process to develop, select and model a viable solution. Thus the students’ primary challenge is no longer “what are the correct buttons to click” (which represents an explicit statement and interpretation of a “learn to model” task, with the associated limited growth in task specific self-regulation), but rather the students need to implicitly utilize their previous knowledge acquired in the course to devise a part (the primary challenge is to design a part that functions under given constraints). The student’s required task interpretation (design) places the software into the correct position
within the engineering design sequence—one of a mere tool, and not an end to itself, allowing the development of higher order task interpretation skills and thus task specific self-regulation, while at the same time requiring increased practice of SV.

The ill structured design problems introduced in the GD section were scaffolded to support the student’s shift in task interpretation from one of explicit software operator to one of implicitly using the software as a design tool (Figure 2), and focused primarily on geometric considerations such as “design an interface between two parts”.

![Diagram of course progression with project deployment sequence.](image)

Figure 2. Course progression with project deployment sequence.

As first project component (Table 1), the students were tasked to reverse model a PASCO beam 41. The students were allowed to manipulate the beam, and were given engineering drawings of the beam so as to be able to model it (in subsequent course iterations the students will be required to take measurements off the physical beam)
Table 1. Relationship between assigned modeling exercise and different stages of deliverables

<table>
<thead>
<tr>
<th>Assignment (given)</th>
<th>Student generated Part</th>
<th>Student generated Assembly</th>
<th>Student generated Drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse modeling exercise</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Geometric design exercise 1</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Geometric design exercise</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>
Once the first modeling task has been completed, and having the beam available as a solid model, the students were then tasked to develop a connector that would allow assembly of 4 beams in a given geometric configuration (Table 1). They did not have access or knowledge of the commercially available PASCO connectors, and thus were confronted with a purely geometric design problem. This geometric design step was administered over two weeks – after the first week, students were asked to present a first draft of the connector and collect feedback from the instructors, and during week 2, students were required to submit their final connector. In parallel, students were learning assemblies, so they were capable of fine-tuning their design to fit the assembly, which was a third deliverable.

Following this step, students were then asked to build on their knowledge of geometric design to develop a connector that would connect the beams in tetrahedral shape (Table 1).

The design of connectors was chosen to entice the students to not only imagine the 3D part, but also the assembly of the entire structure, and discover (and integrate into their design) the symmetry requirements of the respective connector. In particular the tetrahedron challenged students. Many were not able to see that in order to be freely interchangeable and only requiring one single type of connector for all four corners, no two connection arms could lie on the same plane (Figure 3c displays a connector that reflects this mistake).

![Figure 3a, 3b and 3c. Different solutions for tetrahedral connector Geometric Design project.](image)

With the available connectors and the beams, and during the class on assemblies, the students were tasked to assemble both a box using their orthogonal connectors, and a tetrahedron using their tetrahedral connectors. The assembly process uncovered any design flaws of their original beam or connector submission, and required the students to apply an iterative approach to revisit these initial designs to make them suitable for assembly.

During the final weeks of the semester, and in the context of creating engineering drawings and an introduction to GD&T, the students were then tasked to prepare a drawing package of all their project and assembly parts, including assemblies and bill of materials (Table 1).
All student work in these projects was individual.

**3D printing interventions**
The reduced number of 3D printers available and the large number of students in the class have limited the use of 3D printing manipulatives to only supportive roles, primarily used for printing the student-designed connectors (Figure 4) to assemble them into tetrahedron and box assemblies (Figure 5).

![Figure 4. 3D printed Geometric Design Project connectors.](image)

As such, their use has not supported the intended development of spatial visualization skills, but only reinforced them by transporting an already existing design from the virtual to the physical dimension.

![Figure 5. Assembled structure using 3D printed connectors](image)

Even though these limitations hampered the effectiveness of the 3D printing activities, they were appreciated by the students, and have triggered the start of a 3D printing club to be able to further expand their opportunity to use 3D printing.

**Results**
Course assessment:
The normal course assessments were implemented differently in both sections. The transformed section used tests, homework, and in-class assignments, as well as the project stages to compute the course grade, and the traditional section employed tests, homeworks and a project portfolio for the final assessment of the individual grade. While it is not possible to compare these assessment points individually, they may be grouped and combined to express a cumulative grade (over all related assessment points) for each one of the course outcomes (Figure 6).

Figure 6. Course assessment results for each learning outcome

The common learning outcomes are:
At the end of the course, students will demonstrate the ability to:

a) Communicate mechanical designs via freeform, orthographic and axonometric hand sketching
b) Read and interpret mechanical drawings of parts and assemblies
c) Demonstrate familiarity with the fundamental concepts of fits, tolerances, and GD&T
d) Apply a Parametric Solid Modeling CAD package to:
   d1) Construct robust sketches that reflect appropriate design intent
   d2) Construct mechanical parts using extrude and revolve techniques
   d3) Modify parts using fillets, chamfers, holes, patterns, mirror, copy
   d4) Construct assemblies of parts
   d5) Produce engineering drawings of mechanical parts in accordance to a specified drafting standard

Spatial Visualization Assessment:
The assessment of any improvements in student SV skills were conducted using the PSVT:R, where students are required to identify the correct depiction of an object that
has been rotated about one, two or three of its axes. The test was administered to both sections of the course during the first lecture of the semester, and then again during the last lecture of the semester.

Results from the administered PSVT:R pre and posttests (Table 2) indicate that no statistically significant difference between the CG and GD sections has been detected (using two-sample t-test, with n=60 for the control group and n=52 for the Geometric Design section).

Table 2. PSVT:R comparison between CG and GD sections.

<table>
<thead>
<tr>
<th></th>
<th>Geometric Design Group</th>
<th>Control Group</th>
<th>P (two-tail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSVT:R Pre</td>
<td>22.38</td>
<td>22.47</td>
<td></td>
</tr>
<tr>
<td>PSVT:R Post</td>
<td>24.49</td>
<td>24.80</td>
<td></td>
</tr>
<tr>
<td>Change</td>
<td>2.1</td>
<td>2.3</td>
<td>P&gt;0.7</td>
</tr>
</tbody>
</table>

While overall scores for both sections correlate with reported scores in the literature for first year engineering students$^{33,35}$, these results also indicate that the geometric design projects as implemented in the course in its current form show now improvement in student development of SV skills.

Student survey results:
In addition to the quantitative SV assessment, a survey was conducted with the GD group to assess the perceived worth of the geometric design projects and the 3D printing in their development of solid modeling skills. 59 students responded to the survey (although response rate for each individual question varied).

Figure 7. How helpful were the different components in learning the material?
Results indicate that students value the design projects more than simply doing the virtual modeling exercises in the book, however (and as expected), find the tutorials most helpful in learning the material.

The overwhelming majority of respondents (Figure 8) manifested in their written comments that they valued the freedom of designing a personal solution to a common project.

“I liked that we could make our own individual part”
“The freedom to make your own part”
“We get to come up with something instead of just modeling it”
“Mix of creativity as well as basic engineering fundamentals (problem solving)”
“Creating something unique and my own.”

Figure 8. Responses to student question “what did you like most about the design projects?”

The dislike comments primarily reflected on the required time commitment as well as the difficulty in tackling an ill-structured problem (Figure 9). Since this is a first semester class, most students had not been confronted with a college level design prior to the project experience.

“Sometimes it was hard to get started”
“We don’t know what it should be or what it should look like”
“Not getting enough time to perfect them”
“The tetrahedron and its angles were very difficult to understand”
The 3D printing interventions were appreciated and liked (3.6/5, with 5 being very useful for learning the material, and 1 being not useful at all), however student comments indicate that while they perceived them as an interesting exercises, the time and form of how they were applied in the course did not support their learning.

“I don’t think it helped a ton, but it was pretty cool and I learned about 3D printing and design from it”

“It is really cool to see the part I made and what works and what doesn’t”

“I don’t think we would have lost value if our connectors weren’t printed, but it was really cool to have a physical product to see our work”

“They are a good real world representation and are interesting, but I would understand the course just as well without them”

“It was very valuable to actually see it and not have it just on the computer”

Discussion

The grade distribution between the sections and as related to the common assessment of the attainment of the course learning outcomes (Figure 6) reflects adequate attainment of the learning outcomes by both sections. Differences among the sections can be related to different instructors applying a different topic sequencing and grading and deliverables scheme. These class results do not contribute to the understanding of differences in the development of SV skills, however show that student performance was comparable between both sections.

Improving SV skills
Quantitative assessment from the PSVT:R clearly indicates that in its current form, the combination of geometric design projects with limited manipulatives production (introduced after the part modeling, and not in support of the design process) has no statistically significant effect on student’s development of SV skills. A number of can cause this insensitivity, and will provide the basis for the continuation of this work:
1- The form and frequency of the interventions was insufficient to cause a measurable change. During this first iteration of the modified course, a number of practical shortcomings were encountered:
   a. Due to scheduling challenges and the high number of students in the sections, the manipulatives were not used extensively, and only as demonstrators of designed parts, and not in support of visualizing parts before they were drawn.
   b. The low frequency and high effort required for the Geometric Design projects. These projects were of medium complexity, and assigned only twice during the semester, thus limiting their effect on the development of SV skills.

Thus the combined number of specific interventions that aimed at improving SV skills over the traditionally imparted course was limited to four (two manipulatives and two geometric design projects), which may be insufficient.

2- The assessment method of the changes in SV skills is inadequate. The assessment instrument, the PSVT:R, has a long history of validation and thus can be deemed to provide an adequate measure of SV skills. In addition, the collected scores align well with results reported by other researchers. However, there are two shortcomings: first, the PSVT:R is a purely visual test that focuses on rotations, and does not incorporate haptic elements into its evaluation methodology. And second, the purely summative nature of the assessment of SV changes that the pre- and post-testing mode dictates, is unable to detect changes caused by the individual interventions. Thus the possibility that the PSVT:R is too narrowly focused to assess the full effect of the interventions must be considered.

3- The class environment was inadequate. A principal complaint by both faculty and students was that there were too many students in the class, not allowing the necessary personal interaction between the student and the instructor to effectively guide the development process. In addition, the single weekly class period of 3 hours was unanimously viewed as too long.

Self-regulatory effects of the interventions
An additional perspective is rooted in the fact that these GD exercises represent instances of Project Based Learning (PjBL)\(^2\), and is obtained by analyzing the student survey responses. The qualitative responses from the summative student survey indicate interest and appreciation of the geometric design exercises. Upon analyzing the responses to these survey questions, a number of observations can be made:

In response to the question “what did you like about the design projects?”
   • 78% of the 54 responses (Figure 8) manifest that the best-liked feature was the freedom of thought that the open ended projects allowed. This strong response indicates appreciation of independent learning, which can be related to the development of task specific self-regulation\(^7\);\(^43\).
   • The remaining 21% of respondents indicate that their preferred feature of the projects was how it showed the relevance of their work in the greater context of the assembly and the engineering design process. These responses indicate that students viewed the projects not only as stand-alone challenges, but as part of a
more complex engineering environment, which is indicative of appropriate task authenticity in the context of PjBL.

In response to the question “what did you like least about the design projects?” (Figure 9)

- A majority of respondents indicated that their principal challenge were either the technical challenges of capturing the correct geometry and/or translating this into appropriate solid models and technical drawings (54%), followed by the challenges due to the lack of definition of the design problems (19%)

Analyzing this response together with the strong support of the freedom for design in the previous question indicates that, although they found it difficult, the students enjoyed the independent design work of the projects. Appreciation of independently overcoming a moderately difficult task indicates that the design projects constitute mastery experiences for the students, which in turn are principal building blocks for the development of self-efficacy 44.

Further indication of this effect is the subsequent formation of a 3D printing club by a number of the students in the class, in order to continue their design activities in an extracurricular fashion.

No specific assessment of self-efficacy (in particular in relation to the reported gender differences) was conducted, as the survey instrument of this work in progress was designed to only probe for student preferences. Future work however will consider expanding the analysis to include these assessments.

**Conclusion and future work**

The intention of this work-in-progress was to qualify changes in SV caused by the geometric design projects and the 3D printing interventions, and the student survey was merely added to capture the student opinion about the newly introduced course components. These quantitative results indicate that in their present form the Geometric Design and 3D printing interventions constitute a stimulating and interesting component of the course, and are appreciated by the students. However, quantitative results also indicated that the interventions in their current form fail to generate a measurable improvement in SV skills. The detailed analysis of the limited student satisfaction survey has provided an additional perspective on the effect of the interventions. Responses indicate that students find the projects challenging, both for reasons of technical execution and the uncertainties of the design process. At the same time, they strongly manifest their appreciation of the freedom of thought that open-ended design problems provide. Thus the successful completion of a series of challenging projects has served as mastery experiences for the students, which is a primary building block of self-efficacy 44.

Due to the single data point collected in this work-in-progress, it is not possible yet to ascertain specific reasons for the ineffectiveness of the interventions in this form towards developing SV skills, however the insights gained during this first iteration will be used to refine the implementation, and continue the assessment with the help of a control group. Specific planned actions include:
• Increasing the number and reducing the scope of geometric design exercises. During this first iteration, there were only two geometric design project components that were a part in a more complex assembly. In order to require more freeform thinking, future iterations may include an increased number of geometric design exercises, however of reduced scope and duration.

• Include team components. While all work was individual for the first iteration, including team components for a subset of the geometric design exercises may stimulate increased communication with the associated visualization needs. Team components can take on a variety of formats (such as requiring teams to devise the components of a small assembly with each team member responsible for one part, or a team working on the same part), and will require development of effective projects prior to implementation.

• Introduce 3D printed manipulatives earlier and more extensively throughout the semester. This will take on the form of utilizing 3D printing to produce manipulatives for hand sketching exercises, first as a pre-made manipulative to support the visualization of 3D objects to be hand-sketched, and then, later in the course, as design projects for students, where they are tasked to design new hand-sketching exercises (and the associated manipulatives) for the following class. The manipulatives will initially provide improved depth cues and support the visualization of rotated states, and in the advanced design stage will close the loop on the design process.

• Consider different assessment methods beyond the PSVT:R to better quantify changes in the SV of the students. Options include the MCT, MRT, and the Revised Creative Engineering Design Assessment (CEDA), which would expand assessment beyond the SV dimension.

• Develop a more targeted assessment of the effects of the interventions on self-efficacy. This will be accomplished by developing and applying more targeted surveys, and complementing them with student interviews.

In addition to the content modifications described above, the course environment will be changed: The current large class size and single 3 hour session length has constituted a limiting factor for effective teaching, and subsequent iterations of the course will reflect a maximum section size of 50 and a twice-a-week schedule with reduced session lengths.

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