

Coordinating Mind and Hand: The Importance of Manual Drawing and Descriptive Geometry Instruction in a CAD-Oriented Engineering Design Graphics Class

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Abstract

The ability to graphically depict objects in two- and three-dimensional space is fundamental to engineering design practice. Historically, engineers have used pencil, paper, and erasers to draft preliminary sketches and to transform initial drafts into precise production drawings. With the proliferation of computer-aided design (CAD) software programs, instruction in descriptive geometry, and manual drawing has largely vanished from engineering education programs. This article describes the history of instruction in descriptive geometry and manual drawing. It also presents a case study that investigates the contribution of CAD instruction with and without supplemental instruction in descriptive geometry and drawing to the development of students' spatial abilities in an engineering design graphics class.

Introduction

The role of manual drawing and descriptive geometry in engineering instruction

Since the early 1800s, most engineering curricula around the world included instruction in two subjects that were intended to develop the coordination between students' hands and minds: descriptive geometry and manual drawing. Training in these subjects is still an essential part of the engineering curriculum in Asia, and in Central and Eastern Europe. However, with the growth of computer-aided design (CAD), such training has been eliminated from the curricula of many engineering programs in North America (Barr, Juricic, Krueger, Wall, & Wood, 1998; Manning & Hampshire, 2011).

In descriptive geometry classes students learn definitions of geometric concepts (e.g., lines, planes, successive auxiliary views, the intersection of planes, angles between planes, developments, parallelism, perpendicularity, and the relationships between various geometric elements). Using manual mechanical tools such as a compass, ruler, protractor, divider, and triangles, students practice transforming two-dimensional shapes into representations of three-dimensional structure. In schools where such traditional training is required, students learn descriptive geometry and hand drawing principles during their first three semesters, followed by a course on CAD (Kosse & Sanadeera, 2011; Stachel, 2005).

Instruction in manual drawing typically includes training in blueprint reading — reading of working drawings and sketches, basic drafting fundamentals, and techniques; technical drafting — use of drafting equipment, drafting techniques, lettering, geometric con-

struction, multi-view and isometric drawings, sectional and auxiliary views; and dimensioning and tolerance - basic and advanced dimensioning techniques.

Scholars observed that in most American textbooks on Engineering Design Graphics (Bertoline, Wiebe, Miller, & Nasman, 1995; Earle, 1983) that were published when instruction in drawing principles was still part of the engineering graphics design curricula, discussion of descriptive geometry was limited to “standard constructions, such as determining of the true length of a line segment or the intersection of two plane polygons in 3-space” (as cited in Stachel, 2005, p. 3).

The contribution of spatial thinking skills to engineering education and practice

The ability to use spatial thinking skills to translate between two-dimensional and three-dimensional views of an object or structure lie at the heart of engineering design practice. There is abundant empirical evidence that spatial thinking skills are critically important for success in engineering education and practice (Field, 2007; Hsi, Linn, & Bell, 1997; Humphreys, Lubinski, & Yao, 2003; Miller & Bertoline, 1991; Peters, Chisolm, & Laeng, 1994; Sorby, 2009; Sorby & Baartmans, 2000; Webb, Lubinski, & Benbow, 2007).

There is also considerable evidence that spatial skills can be developed and improved through the mastery of sketching in conjunction with the use of modern technology (Connolly, 2009; Contero, Naya, Company, & Saorin, 2006; Hake, 2002; Miller & Bertoline, 1991; Scribner & Anderson, 2005; Sorby & Baartmans, 2000). Lepold, Gorska and Sorby (2001), suggest that individuals who have a strong background in technical drawing are better at using CAD than those without manual drawing experience. The authors argue that this is because those with drawing experience understand the geometry of the design better and understand the limitations of the software.

Gender differences in spatial thinking

There is an evidence for gender differences in spatial thinking, with men outperforming women on many spatial ability tests (Guay, 1977; Hamilton, 1995; Masters & Sanders, 1993; Moe, 2009; Voyer, Voyer, & Bryden, 1995). Empirical evidence suggests that environmental factors, such as childhood leisure activities, affect spatial skills (McGee, 1979; Immekus & Maller, 2010). A psychological factor that has been shown to affect female performance on spatial tasks is “stereotype threat” — the self-doubt that members of a group experience when they are reminded of stereotypes disparaging their group’s abilities in a given domain. This theory suggests that women tend to underperform compared to their male counterparts if there is the chance to confirm the stereotype that they will fail (Hill, Corbett, & St. Rose, 2010; Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005). These gender differences can be greatly reduced by changing the testing environment, changing testing instructions, and providing general affirmation of their skills to women contesting (Bergvall, Sorby, & Worthen, 1994; Contero et al., 2006; Sharps, Price & Williams, 1994).

Drawing to train spatial thinking

In an introduction to his most recent German textbook, Klix noted:

Descriptive Geometry is unique in the way how it promotes spatial reasoning, which is so fundamental for each creative activity of engineers, and how it trains the ability to express spatial ideas graphically so that they become understandable for anybody else. (Klix, 2001, p. 2).

Klix's observations are confirmed by evidence that spatial thinking skills can be improved through training and practice (Uttal et al., 2013). The results from a recent meta-analysis of 217 studies done by Uttal and colleagues suggests that spatial skills are malleable and that spatially enriched curricula can contribute to increasing participation in science, mathematics, and engineering (Uttal et al., 2013). Further, there is evidence that learning to draw is one method that strengthens spatial visualization abilities (Adanez & Velasco, 2004; Ault & John, 2010; Olkun, 2003).

Two relatively recent publications introduce the benefits of integrating manual drawing into a training protocol to improve spatial thinking (Adanez & Velasco, 2004; Olkun, 2003). Olkun (2003) taught middle school students' how to use engineering drawing applications in a geometry classroom. While Olkun (2003) does not provide empirical evidence supporting the use of manual drawings to improve spatial thinking, he suggests activities that require very basic steps for middle school students. Some of the activities Olkun proposes are building solids with different shapes and associating the solids perspective views with the concrete objects. In all proposed activities, manual drawings are not used, rather they are suggested as a context to explain the topics of perspective, orthographic, and pictorial views as well as different views (top, bottom, right, left) and respectively their alignment.

An empirical study done by Adanez and Velasco (2004) investigated the mechanisms through which technical drawing activities improve spatial thinking. In this study, 157 first year engineering students were tested on visualization skills before and after a manual drawing course in their freshman year. More than a third of the students significantly improved their spatial thinking, as measured on 20 items from the Item Visualization Bank (Prieto & Delgado, 2001). Both male ($d = 0.88$) and female ($d = 0.77$) students showed significant gains from pre-to-post instruction measurement. While Adanez and Velasco (2004) described the basic content covered in the technical drawing course - making and interpreting orthographic and pictorial views, imagining sections and details of objects, technical graph expression, dimensioning and efficient manipulation of traditional and computerized instruments of drawing — the authors did not indicate if the students also participated in CAD instruction. The lack of specification about the type of technical hand drawing activities the participants completed, and the presence or absence of CAD instruction, must be considered when evaluating these findings.

The above two publications suggest that engineering educators are now evaluating the potential value of manual drawings in geometry and engineering design graphics and can be interpreted as encouragement of further research on the value of reintroducing descriptive geometry and manual drawing into the engineering design curriculum.

Consequences of eliminating manual drawing and descriptive geometry instruction in engineering design graphics education

With the proliferation of computer-aided design (CAD) software programs, instruction in descriptive geometry and manual drawing has largely vanished from engineering education programs (Guggenheim, 1981; Livshits & Sandler, 1999; Manning & Hampshire, 2011; Pedrosa, Barbero, & Miguel, 2014). Most engineering schools in Northern America teach CAD as a stand-alone course. Typically, the CAD course is the only engineering design graphics course offered within an undergraduate engineering curricula. In the absence of instruction in engineering design graphics, many graduates of engineering programs may have the skills to navigate CAD programs such as Inventor, SolidWorks, CATIA, Pro-engineering, but lack an understanding of essential principles, techniques, and standards used in engineering drawings as tolerance for example.

Engineering educators have noted that reliance on CAD software to the exclusion of instruction in descriptive geometry and manual drawing has negative consequences for the quality of engineering education. Martin-Dorta, Saorin, and Contero (2008) found that reducing credit hours dedicated to engineering drawings and descriptive geometry adversely affects student's ability to develop and improve their spatial reasoning. Several studies have documented a decline in the spatial visualization skills of engineering students since 2003 (Brus & Boyle, 2009; Duff & Kellis, 2009; Hamlin, Veurink, & Sorby, 2008; Knott & Kampe, 2009). Studies suggest that training in technical drawing helps students develop an understanding of solid geometry and improve their expression of thought in two and three dimensions (Field, 2004).

From an anecdotal perspective, the author (a graphics design educator and a former design engineer) has encountered cases in which a practicing engineer's lack of knowledge of engineering drawings has led to the misinterpretation of assembly drawing information. The author has also encountered situations in which recent engineering graduates copy bits from other drawings with identical parts and joints and paste these bits to the new drawing. "*Is that how they teach you at school nowadays?*" is also a common reaction from the senior engineers in cases such as these. Such incidents can also incur additional costs and liabilities for the company.

In industry and higher education, there is a strong concern that complete elimination of traditional drawing would reduce the standard of CAD drawing by students. A strong understanding of manual drawing is important to efficiently utilize and understand the limitations of a CAD software (McLaren, 2008). There is a considerable amount of work

that suggests that though CAD is important, it should be used as an additional aid in teaching and should not eliminate the conventional drawing courses (Bussey, Dormody, & VanLeeuwen, 2000; Chester, 2004; McCardle, 2002; Watkins, 2005). Scholars recommend that an effective CAD curriculum should include all types of drawing with emphasis on freehand drawing techniques and instruction on the basics of orthographic systems through manual drawing. The above studies suggest that learning CAD only fails to adequately prepare students to become proficient designers. Based on the findings from these studies, scholars made recommendations in favor of design and technology education that is focused to equip students with problem solving and self-learning skills, rather than education that is focused to train CAD workstation operators.

Case studies to compare benefits of drawing instruction

On a positive note, there is evidence that instruction in sketching is being reintroduced in the engineering design curriculum (Booth, Taborda, Ramani, & Reid, 2016; Linsey et al., 2011; Schutze, Sachse, & Romer, 2003; Shah, Woodward, & Smith, 2013; Taborda, Chandrasegaran, Kisselburgh, Reid, & Ramani, 2012; Yang, 2009; Yang & Cham, 2007). However, little has been done to investigate how the inclusion of manual drawing and descriptive geometry instruction in a CAD-oriented class can contribute to the development of students' spatial thinking skills. To this end, this case study compares engineering students' spatial thinking skills after instruction in engineering design classes that used identical CAD instruction. In the first class, students received CAD instruction only, while in the second class, the identical CAD instruction was supplemented by weekly instruction in descriptive geometry and manual drawing.

Method

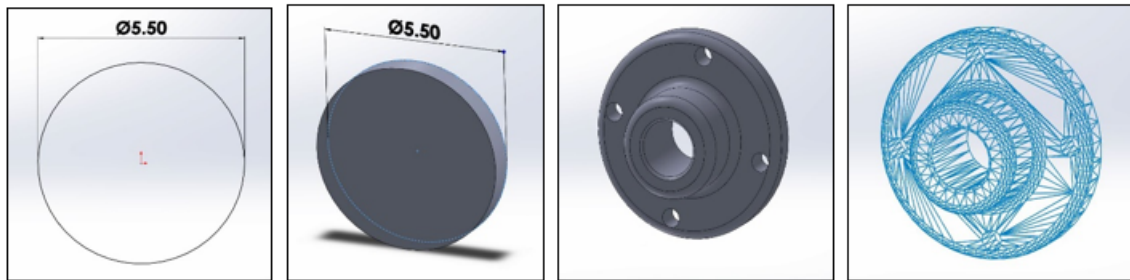
In the Spring of 2014 the author taught Engineering Design Graphics, a junior level course in engineering design in which students learned CAD modeling using Solidworks software. This is the only engineering design graphics course offered within this institution undergraduate engineering curricula that includes CAD instruction. The instructor also taught the same Engineering Design Graphics course in the Spring of 2015, but supplemented identical instruction in Solidworks software with lectures and activities on descriptive geometry and topics related to spatial thinking, including perspective thinking, orthographic views, sectional views, dimensions and tolerance. This supplemental instruction was presented for 75 minutes per week over 15 weeks.

Solidworks CAD Instruction

It should be emphasized that the CAD instruction was constant across both classes. Students learned modeling features of SolidWorks and the role of this software as an integrated engineering design tool. To reflect the new user modeling interface and features of the SolidWorks software, the following textbook in both classes served as the students' tutorial, *Introduction to Solid Modeling Using SolidWorks* (Howard & Mus-

to, 2013). Homework problems were assigned once per week and were due one week later. Class homework was from the textbook.

The following is an example of a CAD lesson presented by the author. Instruction: To design a flange, students were first instructed to choose a modeling technique, create 2D sketches using Solidworks, then extrude and define the curves to create 3D geometry. Next, the students were introduced to the fact that while extruding, there is increasing weight of the object that allows the designer to control the desired amount of material. They were instructed to erase some of the unnecessary parts to save some printing time and material. The instruction ended with teaching students how to save their drawing as a STL file to be sent to a 3D printer. In the following CAD lab, the students learned how to complete the above tasks (Figure 1). In addition to the homework assignments, students had to complete a midterm and final project, both involving submission of assembly drawings. Table 1 lists the CAD assignments through the whole semester and Figure 2 and Figure 3 present examples of students' assembly CAD drawings.



*Images are drawn by Sathya Narayanan, a graduate research assistant in the ACE(D) Lab.

Figure 1. Example of a Flange design using CAD. A flange is created in several steps using CAD. Students also learn how to create the STL file

Table 1
CAD Course topics and assignments

Basic Part Modeling Technics	HW1: Creation of a flange HW2: Creation of a pulley
Engineering Drawings	HW3 – HW6: Creation of fully-formatted, dimensioned, and annotated engineering drawing of: a beam, bracket, pan, hinge pin
Parametric Modeling Technics	HW7: Threaded rod
Creation of Assembly Drawings	HW8: Creating parts for door assembly
Assembly Drawings	Midterm Project: Hatch Assembly Final Project: Cam Drive Unit Assembly

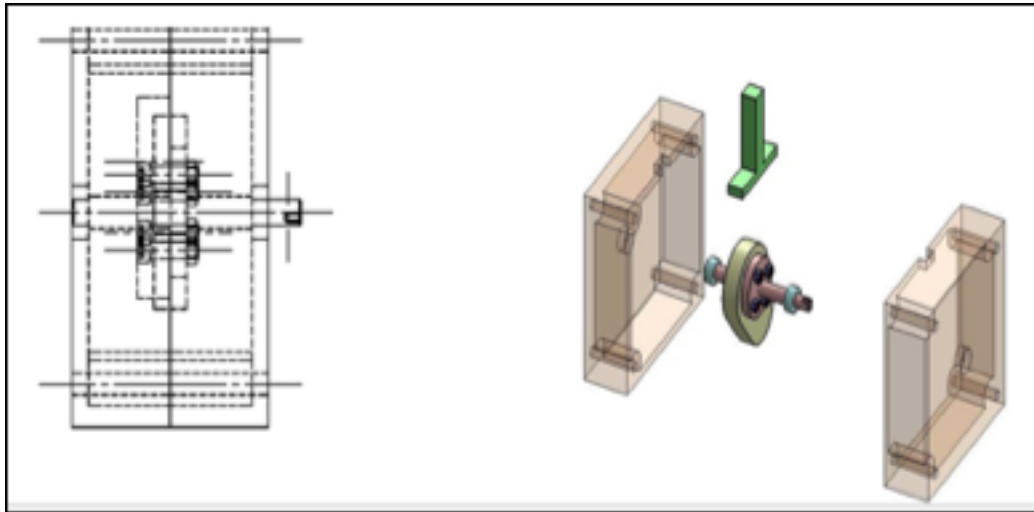


Figure 2. Examples from students' CAD assembly drawings

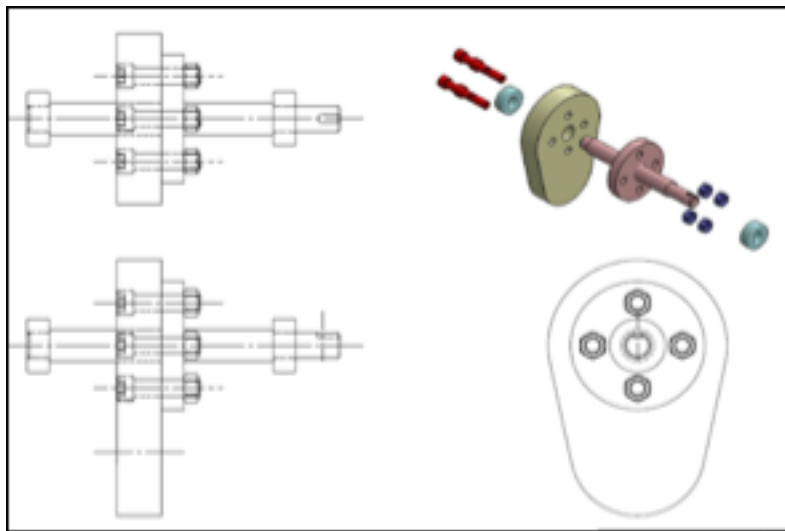


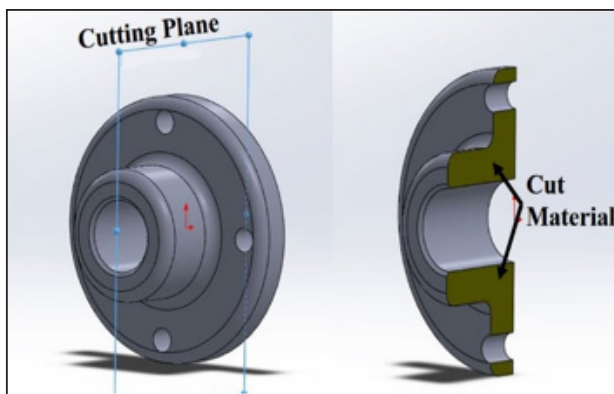
Figure 3. Examples from students' CAD assembly drawings

Manual Drawing Instruction (Perspective thinking, Orthographic View, Sectional View, Dimensions and Tolerance)

In both semesters, the class met once a week for 75 min (15 sessions total). In the second offering of the class, instruction on manual drawings and descriptive geometry was during the lecture. Students were instructed on manual drawings and drew geometrically shaped objects with three parallel drawing systems: 1) Orthographic (2D -- front, side, top views), 2) Isometric (3D), and 3) Frontal and Plan Oblique (3D). Students completed manual drawings assignments using only pencil and paper. They were required to bring to class a wooden #2 pencil and white 8 ½ x 11in. paper without grid lines, and

were discouraged to use rulers, T-squares, triangles, or any computer software to complete these assignments. The Solidworks instruction was done in the lab portion of the course. The following is a list of the descriptive geometry topics and manual drawing instructions presented in the CAD + manual drawing class: descriptive geometry, engineering drawings, orthographic view, isometric view, sectional view, dimensioning, tolerance, and blueprint reading.

The following is an example of instructions given on manual drawing introducing the topic of sectional views: In three 75-minute lectures, the instructor explained how engineers use sections to represent the interior structure of an object that cannot be clearly defined by exterior views. In the first lecture, the instructor explained that by taking an imaginary cut through the object and removing a portion between the viewer and the cutting plane, the inside features of a three-dimensional object are clearly seen (Figure 4). In the second lecture, the instructor discussed and demonstrated engineering design conventions for drawing sections (Figure 5). In the third lecture, the instructor demonstrated how to read engineering drawings of different sectional views. This type of classroom instruction was chosen with intention to allow the transmission of explicit declarative and procedural information about sectioning through verbal and visual modalities. One goal of the course was that students develop an understanding of the application of these techniques to solving practical problems in design, engineering, and manu-



*Figures 4 and 5 are drawn by Sathya Narayanan, a graduate research assistant in the ACE(D) Lab.

Figure 4. Illustration of cutting plane and resulting full section view of the mechanical object

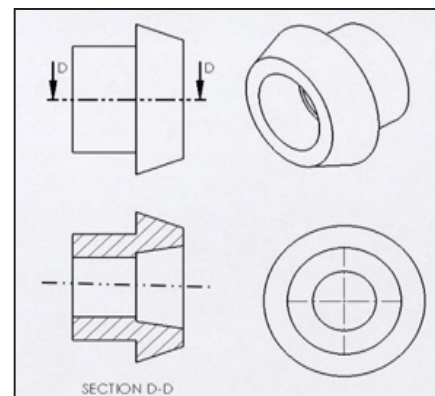


Figure 5. Types of sections

facturing. To this end, students completed three sets of manual drawing assignments at the beginning, middle, and at the end of the semester. These assignments required students to demonstrate their understanding of geometric construction, various view selections, and competency in drafting principles in plane geometry. In addition, the assignments required students to demonstrate competency in technical sketching, orthographic projection theory and practice, auxiliary views, and competency in sectioning, dimensioning, and tolerance.

The first set of activities comprised a booklet with 10 drawing problems, instructions of what to sketch and a description of the material composition of the object. Students completed the activity individually at the beginning of the semester.

The second set of drawing activities were performed in-class following an extensive lecture on drawing sectional views. For the second activity, each student received a booklet with 10 drawing problems, instructions of what to sketch and a description of the material of the part. Students completed the assignment individually at mid-semester.

The third set of drawing activities was also completed in-class. Each student received a booklet with five drawing problems, instructions, and a description of the material of the part. Students completed the assignment individually at the end of the semester. Some of the mechanical objects were present in the classroom. Students were encouraged to investigate and manipulate the objects. Examples from the students' assignments are presented in Figure 6. The drawing assignment problems were assigned from Kirstie Plantenberg's textbook — *Engineering Graphics Essentials* (Plantenberg, 2010). Throughout the semester, during lecture time, the instructor brought a variety of mechanical objects and students were invited to draw these objects. These artifacts were typical tools, mechanical part, and simple machines engineers would interact with throughout their daily practice. The materials of these objects varied from steel, to iron, or plastic; the manufacturing process of these objects also varied from casting, machining, to the use of additive manufacturing. Students were invited to do manual drawings including for example, different types of view — isometric, orthographic, sectional.

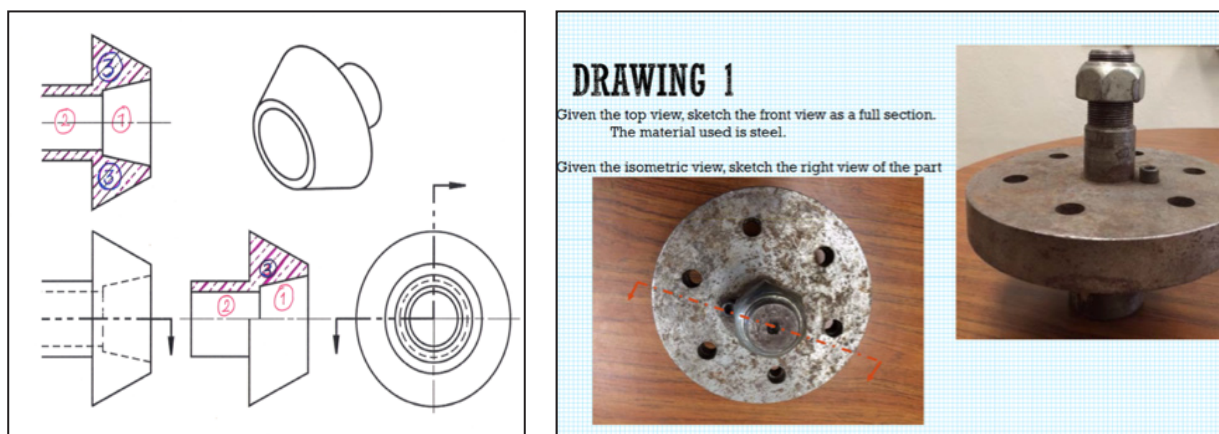


Figure 6. Examples from students' freehand technical drawing assignment

In both classes, students were encouraged to draw anytime and anywhere, and to submit their drawings to the instructor. However, the instructor received drawings only from students in the CAD + drawing instruction class. Examples of manual drawings that

student completed in their free time (out of the classroom) are provided below in Figure 7. Examples of students' sketches of their favorite objects are shown in Figure 8.

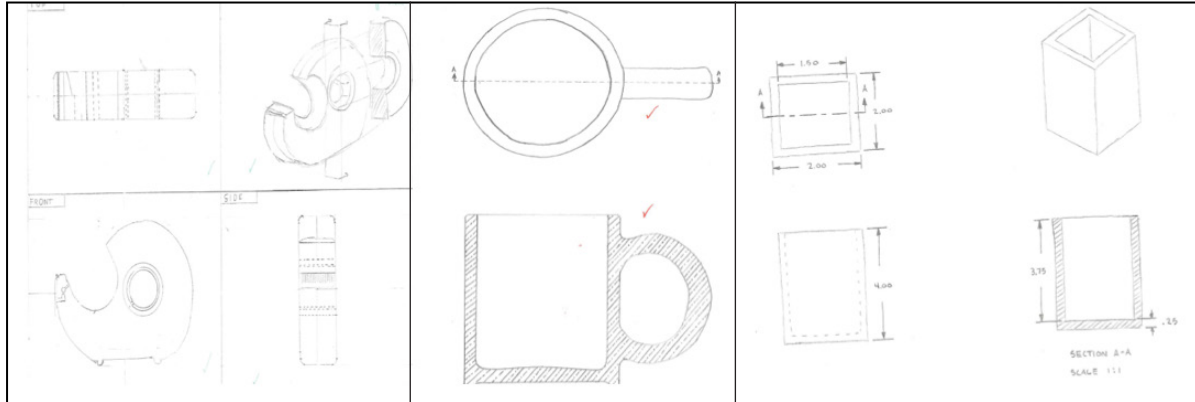


Figure 7. Examples of students manual drawings from the CAD+drawing class

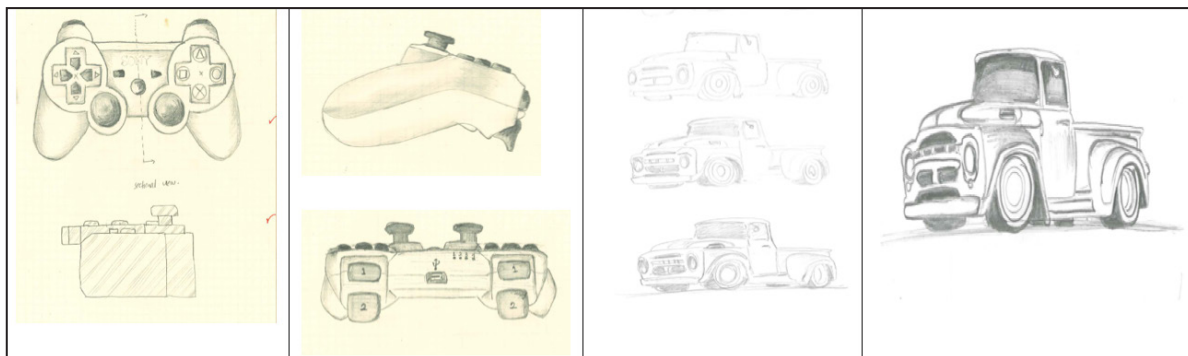


Figure 8. Examples of students drawings of their favorite objects from the CAD + drawing class

On the first and last day of the course, in both semesters, students took spatial thinking tests.

Participants

CAD instruction only (CAD only).

One hundred and fifteen students ($N=115$, $M=94$, $F=21$) enrolled in Aerospace and Mechanical Engineering in Spring 2014 received instruction on CAD.

CAD instruction and manual drawing (CAD + drawing instruction).

One hundred and twenty-nine ($N=129$, $M=104$, $F=25$) students enrolled in Aerospace and Mechanical Engineering in Spring 2015 received instruction in CAD and manual drawing.

Measures

Purdue Spatial Visualization Test: Rotation.

In both classes, students took the Purdue Spatial Visualization Test-Visualization of Rotations (PSVT:R) at the beginning and end of each semester. The PSVT:R consists of 30 questions that require participants to solve problems about developments, rotations, and isometric views (Guay, 1977). The pictorial views in the test are based on isometric drawing principles. Two views of an object (an initial view and a rotation of the same object) are presented to demonstrate a particular class of rotation. A second object, along with five rotated views, is displayed, beneath the first set of objects. The participant's task is to choose the rotated view in the second set of objects that has resulted from the same rotation as the shown in the given model.

Santa Barbara Solids Test (SBST).

In the CAD + drawing class, students also completed the Santa Barbara Solids Test as a pre- and post-measure. The Santa Barbara Solids Test (SBST) (Cohen & Hegarty, 2012) is a 30-item multiple choice test, participants are asked to identify from four answers the two-dimensional shape that would result if the three-dimensional object were sliced at the indicated plane. The 30 test figures comprise three levels of geometric complexity. Simple figures are single geometric solids (a cone, cube, cylinder, three-sided prism, or four-sided pyramid). Joined figures are composed of two simple figures joined at their edges. Embedded figures are composed of one simple figure enmeshed inside of another. Half of the figures have cutting planes that are orthogonal (horizontal or vertical) to the figure's main vertical axis; the other half have cutting planes that are oblique to the main vertical axis. All the figures are oriented with their vertical axes perpendicular to an imagined horizontal tabletop.

Results

Pre-to-post PSVT:R (CAD only and CAD + drawing classes)

Students in the CAD only group showed no significant changes in performance on the PSVT:R from pretest ($M=.77$, $SD=.15$) to posttest ($M=.76$, $SD=.12$). In contrast, in the CAD + drawing class there was a significant increase in PSVT:R performance from pre- ($M=.74$, $SD=.19$) to posttest ($M=.81$, $SD=.16$), $t(71) = -2.42$, $p = .018$.

Santa Barbara Solids Test (CAD + drawing class)

Across genders, there were no significant differences in SBST performance from pre- ($M=.75$, $SD=.21$) to posttest ($M=.78$, $SD=.21$). However, for females only, there was a significant difference in pre- ($M=.67$, $SD=.24$) to post- ($M=.73$, $SD=.23$) SBST performance $t(25) = .2.06$, $p<.05$.

Discussion

Students in the CAD instruction + drawing class (Spring 2015) showed a significant improvement from pre-to-post PSVT:R while there was no such improvement in the students who received CAD instruction only. These results suggest that instruction in standard orthographic projection and descriptive geometry alongside a traditional CAD instruction in an Engineering Graphics Design course can improve engineering students' spatial thinking.

While there were no significant pre-to-post improvements overall on the SBST, female students only in the CAD + drawing class significantly improved their pre-to-post instruction performance on the SBST.

One plausible alternative explanation for this significant difference is that the SBST test explicitly shows the cutting plane while in the PSVT:R, participants need to mentally place that plane. Considering that all students were instructed on sectional views and engaged in several sectional view drawing assignments with the plane shown (not imagining it), it helped particularly female students (as research shows that female students in general follow instruction more than their male classmates). This claim was supported by the results of the drawing assignments performance - female students' drawing scores were higher than male students' drawing scores as the instruction progressed through the semester.

Another consideration is that stimuli used in the PSVT:R are more geometrically complex than those used in the SBST. A third, and important difference between the two measures is that identifying a cross section, as represented in the SBST, is a multi-step process. Steps: encoding the stimulus, mentally slicing the figure, dispensing mentally with the unneeded (cut-away) part, either then changing one's view perspective, or mentally rotating the object (Cohen & Hegarty, 2012).

One plausible explanation or another, the above results suggest that supplemental instruction in descriptive geometry and manual drawing may be particularly advantageous for females.

The case study participants who received instruction in manual drawing and descriptive geometry were Aerospace and Mechanical Engineering major students. Given the requirements for spatial reasoning in engineering education and practice, it is likely that students in a variety of disciplines (e.g., mechanical, plastics, industrial, piping, aerospace, marine, civil, and structural engineering) would benefit from such training.

A future research goal is to run a more controlled study to confirm the findings of this case study. Additional investigations could examine the relative benefits of instruction for females vs. males. Further studies are planned to investigate how to best integrate

spatial visualization training exercises into engineering instruction. To support this effort, the author is developing novel drawing problems and a spatial visualization training protocol that incorporates the structural complexity inherent in real mechanical objects. A long-term goal is to apply these drawing activities through the engineering and STEM curriculum.

As manual drawing has been replaced by CAD, many engineering educators believe that descriptive geometry is an obsolete part of the curriculum. However, a review of the recent literature shows that individuals with expertise in descriptive geometry can make extended use of CAD programs as the communication is usually based on views only. Complex and sophisticated modeling programs require a knowledge of the geometric properties of objects to create shapes, machines, and to understand their relations in space. It will take a long time for an inexperienced designer to become an expert only by using CAD to the exclusion of traditional tools - instruction on manual drawing, including blueprint reading, dimensioning, and tolerance compliments students understanding of complex engineering drawings.

Instruction in descriptive geometry enhances the ability to comprehend spatial objects from given plane views. Further, training in descriptive geometry teaches students how to abstract the geometric properties of a variety of geometric shapes. Exposure to multiple views of and projections of geometric objects enables students to more easily imagine the essential properties of novel spatial structures.

Conclusion

In conclusion, the author recommends that descriptive geometry and manual drawings be included in the undergraduate engineering curriculum, especially where learning CAD programs is the only engineering design graphics instruction undergraduate students receive through their four years of college education. Learning descriptive geometry and manual drawing will not only help students connect hand and mind, but will also contribute to the development of engineers who can connect the dots and understand the relationships between finished drawings and geometric principles. The future of design and manufacturing is 3D solid modeling — graduating engineering students who understand these principles and concepts should be critically important for both educators and industries.

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Acknowledgments

The author would like to thank all students participating in the study and the ones who shared their drawings for this publication. The author would also like to express her gratitude to Cheryl A. Cohen, PhD for her thoughtful feedback and keen eye, which helped to keep my passion for drawings logical, yet avid.

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