IMPROVING ENGINEERING SKETCHING ABILITIES AND THE BENEFITS FOR ENGINEERING DESIGN

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IMPROVING ENGINEERING SKETCHING ABILITIES AND THE BENEFITS FOR ENGINEERING DESIGN

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To Chloe and Margot whose love and support I could not have done this without.

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SUMMARY

Freehand sketching is a critical tool for engineering design. Particularly during conceptual design, sketching is leveraged for many essential tasks. Freehand sketches allow a designer to communicate complex or ambiguous ideas to teammates, sketching offloads working memory allowing a designer to develop further concepts, and freehand sketching supports a critical feedback loop that enables design decisions to be made in real time. Sketching is a free and flexible tool for visual representation, and more frequent sketching has been shown to correlate with positive design outcomes. However, even given the importance of sketching for the design process, sketching is only taught minimally (as little as three weeks of instruction in a single course) in the engineering curriculum. It has been noted in literature for some time that engineers have the need for both formal drafting skills and informal freehand sketching skills. Given the lack of focus on developing this critical skill, do engineers have the skills necessary to reap the benefits of sketching in the design process? This dissertation seeks to further understand the importance of sketching skills for engineering design. The topic is approached from two sides: how to improve sketching education and understanding the benefits of sketching skills for engineers. The first study explores improving sketching skills through modified freehand sketching instruction, an intelligent tutoring software for sketching, and instruction length. The second study looks at the relationship between sketching skills and idea generation abilities. The final study examines sketching behavior in design project courses, and to what extent they are predicted by sketching skills and other measures. The results of this dissertation provide the costs of resources associated with improving sketching skills and

benefits gleaned from improving them. This cost-benefit comparison helps to inform the importance of practicing sketching skills for engineers and engineering education.

CHAPTER 1. INTRODUCTION

Engineering design is a visual task (Ferguson, 1994). The majority of an engineering design cannot simply be described by words, but rather designs necessitate visual representation to convey meaning and reach a shared understanding (Ferguson, 1994). During the conceptual design phase, designers need a fluid and flexible form of representation to explore and test ideas. Sketching affords many benefits for early-stage concept exploration: sketching is fast, it requires minimal cognitive resources, it's tolerant of inaccuracy or ambiguity, and sketching provides (unexpected) cues for design (Goldschmidt, 2014). Sketching has been widely documented in literature as a powerful tool for design. Sketching offloads working memory (Bilda & Gero, 2005), sketching is essential for communication (Goldschmidt, 2007), and sketching enables a feedback loop that helps designers evaluate and improve their ideas (Goldschmidt, 1991; Suwa, Gero, & Purcell, 1998). Further, more frequent sketching during the design process has been shown to positively correlate with design outcomes (Das & Yang, 2022; Song & Agogino, 2004; Yang, 2009). Sketching positively impacts the design process in measurable ways. It is a powerful tool that engineering designers should be encouraged to utilize more frequently.

Design is central to the process of engineering (Dieter & Schmidt, 2009). Design is the creating of new solutions to new or existing problems (Blumrich, 1970; Dieter & Schmidt, 2009). Typically, the engineering design process is broken down into three steps: (1) conceptual design, (2) embodiment design, and (3) detail design (Dieter & Schmidt, 2009). Conceptual design involves defining the problem to be solved, gathering relevant information about the problem and previous solutions, generating concepts, and evaluating concepts to move forward with (Dieter & Schmidt, 2009). Embodiment design involves determining the specific components and configurations as well as any parametric design that needs to take place to determine exact sizes and tolerances (Dieter & Schmidt, 2009).

And finally, detail design involves creating engineering drawings and any final prototyping or testing that needs to take place before manufacturing (Dieter & Schmidt, 2009).

Visual representation in the early stages of design is tangibly different from visual representation in the embodiment and detail phases of design. These distinct modes of representation highlight the need for designers to be trained in both formal drafting skills and less rigid freehand sketching skills (Ullman, Wood, & Craig, 1990). Ullman et al. (1990) noted this decades ago, but the need still remains. There are many fluid and flexible affordances of sketching during conceptual design (Goldschmidt, 2014) that CAD has yet to fulfill. However, in engineering education, teaching freehand sketching skills can be prioritized much lower than teaching CAD. While no formal review of sketching in engineering curriculums has been conducted, many researchers have noted the same trend – that engineering students receive little to no formal training in sketching (Linsey et al., 2011; Marklin Jr, Goldberg, & Nagurka, 2013; Martin-Erro, Somonte, & Escudero, 2016; Schmidt, Hernandez, & Ruocco, 2012; Song & Agogino, 2004; Taborda, Chandrasegaran, Kisselburgh, Reid, & Ramani, 2012; Uziak & Fang, 2018; Westmoreland, Ruocco, & Schmidt, 2011; Yang & Cham, 2007). There seems to be a disconnect between the importance of sketching in engineering design and the importance of sketching in engineering education. While the importance of sketching to the design process is well documented, there have been few studies on the role that sketching skills play in design tasks. If sketching benefits design, does how well designers sketch influence the effect size of those benefits? Only a few studies have explored this topic. One set of studies found that sketch quality influenced perceptions of concept quality and concept creativity (Kudrowitz, Te, & Wallace, 2012; Kwon & Kudrowitz, 2018). Ideas with higher quality visual representations were perceived as more creativity and higher quality concepts (Kudrowitz et al., 2012; Kwon & Kudrowitz, 2018). Another set of studies evaluated engineering students sketching ability and then observed their sketching behavior through design logbooks in a design project course. The sketching logbook studies found that higher sketching skills positively correlate with more frequent sketching during the design process (Das & Yang, 2022; Yang & Cham, 2007). Engineering designers with stronger sketching skills are more inclined to sketch during the design process. Beyond this, there is very little research exploring the importance of sketching skills for the engineer.

Further understanding of the importance of this skill is critical for both practicing engineers and engineering education. If engineering students are not being equipped with the sketching skills needed to access the benefits of sketching for design, this could shortchange designers in the long run. Inhibited sketching skills could put a strain on designers' communication, hinder concept exploration, and increase the cognitive load of design. Understanding the impact of sketching skills on the different aspects of design will help to better prioritize sketching in engineering education. The origins of engineering design had a larger focus on artistry and other soft skills such as Leonardo da Vinci (Ferguson, 1994).Qualitative soft skills, such as sketching, often involve more personalized feedback and more apprenticeship-type mentoring, which is difficult in the context of modern engineering education. These softer skills used to be core to the very nature of design but have since taken a back seat. Further insight into the impact of these soft skills will help guide the future of engineering education to ensure engineering students are not being disadvantaged in their design skills.

The goal of this dissertation is to understand the role of sketching skills in engineering design. Herein, I present three studies focused on how sketching education can be improved for engineering students, and the influence of sketching skills on different design tasks. It is critical to address both difficulties in teaching sketching in the context of engineering curriculums and further understanding of the importance of sketching skills. Approaching the impact of sketching skills from both perspectives will offer a cost benefit analysis that will inform both how difficult it is to improve engineers' sketching skills and how much there is to gain from further investing in this skill. The first study in this dissertation looks at improving sketching skills for engineering students. The second and third explore the impact of sketching skills on design. The second study examines the relationship between sketching skills and idea generation abilities. The final study examines the relationship between sketching skills and other factors and sketching behavior during design project courses.

1.1 Improving Engineering Freehand Sketching

The first study examines improving engineering sketching skills through three pedagogical adaptations: (1) type of sketching instruction, (2) amount of sketching instruction, and (3) the use of intelligent tutoring system to aid in the delivery of and feedback on sketching homework assignments. First, type of instruction for engineers was examined. Two-point perspective sketching techniques adapted from the industrial design program were introduced to the engineering curriculum and compared against a traditional engineering sketching instruction approach. Perspective sketching puts much greater emphasis on freehand sketching skills compared to what is traditionally taught (E. Hilton et al., 2016; Hilton, Linsey, Li, & Hammond, 2018). Second, I looked at amount of sketching instruction comparing the impact of similar sketching instruction administered at two institutions for different lengths of time. One university provides 3 weeks of sketching instruction and the other provides 5 weeks each in a 3-hour course. This comparison provides clearer understanding of how much instruction is necessary to alter engineers' sketching abilities. Lastly, the intelligent tutoring software, Sketchtivity, was introduced to offload some of the work needed by instructors and to provide greater feedback and enhance motivation. Sketching is often taught in large entry-level engineering courses (~50 students) where individualized feedback is difficult to provide. Sketchtivity teaches the basics of perspective sketching and provides students with feedback to help them improve. This homework delivery system is compared against homework on paper to understand Sketchtivity's ability to improve students sketching skills and to decrease the workload for the instructors. These three interventions (type of instruction, length of instruction, and intelligent tutoring software) will provide clearer insight into methods for improving sketching abilities in the context of engineering education.

1.2 The Role of Sketching Skills and Sketch Detail in Idea Generation

Sketching is most critical in the early stages of the design process. Many solutions are considered in rapid succession, and concepts are created, built upon, combined, and thrown out repeatedly. Sketching serves as a representation tool to quickly communicate, document, and evaluate design ideas. Within early design, idea generation is most dependent on sketching, particularly in fields like mechanical engineering where problems are physical in nature and often require challenging visual-spatial reasoning. The second study investigates the relationship between sketching ability and idea generation ability. Engineering students were evaluated in an entry-level engineering design and graphics course. Students were given independent tasks of sketching skills and idea generation to examine relationships between the two constructs. The course involves 5 weeks of sketching instruction. Students were evaluated on both before and after the sketching instruction to track their improvement across all measures. This study also introduces a new set of measures called *sketch detail* to serve as a mediating variable between sketching skills and idea generation. This measure is based on previous measures in literature "sketch complexity" and "level of detail" (McGown, Green, & Rodgers, 1998; Song & Agogino, 2004). Sketch detail is intended to evaluate the amount of information shown in the idea generation sketches. This measure likely mediates the relationship between sketching skills and ideation effectiveness – sketch skills influence sketch detail, and sketch detail, in turn, influences idea generation. Examining regressions between sketching skills, sketch detail, and idea generation will provide insight into the role of sketching skills for idea generation.

1.3 Predictors of Sketching Behavior

Lastly, the third study examines regressions between sketching skills and a range of other predictors and sketching behavior in engineering design project courses. Increased sketching frequency is connected to better design outcomes (Das & Yang, 2022; Song & Agogino, 2004; Yang, 2009). Currently, engineering students are sketching at a low quality level during the design processes (Westmoreland et al., 2011). Understanding predictors of students sketching behaviors will shed light on why students sketch, which should open doors for interventions to improve sketching behaviors. In this study, students were evaluated over time while completing an engineering undergraduate degree. Students sketching skills and spatial skills were evaluated in an entry-level engineering design and graphics course. In the graphics course, students received one of two sketching instructions: traditional engineering sketching instruction or perspective sketching instruction. Then students sketching behavior was tracked over time in project-based courses. Students were surveyed on how frequently and for what reasons they used sketching in both a sophomore-level design course and a senior-level capstone design course. In the project courses, students were also surveyed on their engineering design self-efficacy (EDSE) (Carberry, Lee, & Ohland, 2010) and demographics. This study examines the degree to which sketching behavior is predicted by all of the above measures: sketching skills, spatial visualization skills, sketching instruction, design self-efficacy, and gender. Understanding how these factors predict sketching behavior can be leveraged to increase the use of sketching in future designers. Increasing the frequency of sketching should have positive benefits for designers and design outcomes.

1.4 Research Questions

The three studies that comprise this dissertation are guided by the following research questions.

RQ1. *To what extent can engineers' sketching abilities be improved through simple changes in the curriculum?*

1.1. *To what extent does perspective sketching instruction improve freehand sketching skills?*

1.2. *To what extent does an intelligent tutoring system such as Sketchtivity improve freehand sketching skills?*

1.3. *To what extent do students enrolled in a class with 5-weeks of instruction in sketching have significantly higher freehand sketching skills and sketching self-efficacy than students enrolled in a course with 3-weeks of instruction?*

RQ2. *To what extent do sketching skills predict ideation effectiveness?*

2.1. *To what extent do sketching skills and drawing self-efficacy predict ideation effectiveness?*

2.2. *To what extent does sketch detail mediate the relationship between sketching skills and ideation effectiveness?*

2.3. *To what extent does perspective sketching instruction improve sketching skills, drawing self-efficacy, sketch detail, and ideation effectiveness for entry-level engineering students?*

RQ3. *What factors influence sketching behavior in a design course?*

3.1. *To what extent does sketching behavior differ between a sophomore-level and capstone design course?*

3.2. *To what extent do the following constructs predict sketching behavior during a design project course?*

3.2.1. Sketching Skills

3.2.2. Type of Sketching Instruction

3.2.3. Spatial Visualization Skills

3.2.4. Engineering Design Self-Efficacy

3.2.5. Gender

CHAPTER 2. BACKGROUND

Visual representation is absolutely essential for design. The need for visual representation for engineering is dichotomous – engineers have the need for both formal drafting skills as well as informal freehand sketching skills (Ullman et al., 1990). These informal freehand sketching skills are of critical importance in the conceptual stages of design as designers create, evaluate, and refine ideas. Sketches serve as dynamic stimuli that can prompt designers to form new ideas in group idea generation (Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001). The messiness of sketches allows them to be misinterpreted, which can lead to unexpected design concepts. Sketching is often contrasted with CAD which is construed as overly rigid for early-stage design. However, a recent study showed that designers when given the choice to use tools freely will switch back and forth between CAD and sketching leveraging each tool for its afforded usefulness (Shih, Sher, & Taylor, 2017).

Sketching offloads the working memory of the designer freeing them up to continue in the design process (Bilda & Gero, 2005). The fast and fluid visual representation reduces the need to visualize every design decision mentally. These external visuals give designers a space to perceive the work they've done so far and make further design decisions and alterations (Suwa et al., 1998; Suwa & Tversky, 1997). Sketching allows designers to visually evaluate their solutions in real time during idea generation allowing fast iteration to better solutions (Schütze, Sachse, & Römer, 2003). Sketching also enables expert designers to identify restructuring design moves that are less intuitive more effectively (Verstijnen, van Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998). Lastly, sketching supports these functions of developing ideas all the more by its inherent cognitive benefits: time effectiveness, requiring minimal cognitive resources, being tolerant of incompletion or inaccuracy, and providing (unexpected) cues (Goldschmidt, 2014). Sketching is a powerful tool for design in many ways.

Given the clear benefits of sketching in the design process, it is not surprising that there is strong evidence that more frequent sketching in design correlates with positive design outcomes. Through studies of design logbooks several studies have shown a relationship between number of sketches and project outcomes, although with slight differences between the findings. Song and Agogino (2004) found a positive correlation between the number of sketches generated during the design process and design project ranking in an engineering design course. They found that this correlation was strongest with sketches completed in the later part of the design process. Yang (2009) similarly found that number of sketches correlated with final design grades. However, they only showed a relationship with dimensioned sketches completed earlier in the design process. Yang (2009) posited that dimensioned sketches earlier in the process were connected with prototyping early on, which helped designers make improvements more quickly. Lastly, this finding was corroborated by Das and Yang (2022) who found that number of sketches throughout a project course correlated positively with score on the final project. Their study also looked at sketch quality, and they found that sketching frequency was correlated with sketch quality, but sketch quality was not correlated with design outcomes.

Few studies have examined the role that sketching skills play in design. The studies described above demonstrate the power that sketching can have in design, but it is still unknown what degree of sketching skills are needed to reap those benefits. There is some evidence that sketching skills correlate with using sketching more frequently during design. Yang and Cham (2007) measured sketch quality through two tasks: a drawing facility task that involved sketching a live model, and a novel visualization task that involved sketching a three-dimensional object from a verbal description. They found a positive correlation between sketching skills and frequent use of sketching, which is expected but important because frequency of sketching corresponds to positive design outcomes. Das and Yang (2022) measured sketch quality by evaluating conceptual design sketches from logbooks on metrics for line smoothness and proportion/accuracy. They found that sketching skills measured this way also correlated positively with frequency of sketching during the design project. Sketching skills also play an important role in how designers perceive concepts. The sketch quality of an idea influences how designers perceive both the idea quality and creativity (Kudrowitz et al., 2012; Kwon & Kudrowitz, 2019). There is a positive correlation between the perceived goodness of a concept and the skill with which it was represented. This creates a potential bias in the design process. If the representation of an idea is better, then designers perceive that idea as favorable.

It is understandable that more work has not been done with sketching skills because there is very little consensus on how to evaluate sketching skills (Merzdorf et al., 2022). Prior work on teaching freehand perspective sketching in engineering courses demonstrated that six weeks of sketching instruction meaningfully improved students sketching skills, but three weeks of instruction had negligible impact on actual skill (Weaver, Ray, et al., 2022). However, drawing self-efficacy improved in both instruction conditions showing that even a small amount of sketching instruction can boost confidence. Sketching instruction plays an important role in engineering education beyond just improving skills. Traditional engineering sketching exercises have been shown to have a positive impact on spatial skills (Sorby, 2009). Improving spatial skills benefits performance in other engineering courses and improves educational outcomes for female students in engineering (Sorby, Veurink, & Streiner, 2018). Sketching instruction focused on freehand sketching improves spatial skills equally well compared to traditional engineering sketching instruction focused on producing isometric and multi-view orthogonal images. Freehand sketching instruction also has the added benefit of equipping students with better tools for visual representation (Hilton, Linsey, et al., 2018).

CHAPTER 3. IMPROVING ENGINEERING FREEHAND SKETCHING

The focus of sketching education for engineers is changing. Traditional engineering sketching education focuses on isometric and orthographic views drawn on graph paper or dot grid paper. The purpose of those skills was originally engineering drafting, and more recently, their purpose has become gaining practice in visuospatial reasoning and preparing students to work with CAD tools by familiarizing them with switching between different drawing views. This type of sketching instruction underemphasizes developing freehand sketching skills, which are critical for engineers. Freehand sketching is the ability to draw without the aid of special paper or tools, and this allows engineers to represent their ideas more fluidly in the design process. Ullman in 1990 called out the need for sketching skills in engineers as two-fold – engineers need to be trained in both drafting skills and "informal" or freehand sketching skills that can be used to represent more abstract concepts (Ullman et al., 1990). Now that engineering drafting is entirely computer-driven, sketching curriculum in engineering schools would be more practically useful if it were focused on preparing future engineers to freehand sketch their design concepts.

To create opportunities for engineering students to develop freehand sketching skills, mechanical engineering instructors working with industrial design instructors developed a freehand perspective sketching curriculum based on the industrial design sketching that is well-suited for the needs of engineers. Two-point perspective has many advantages over what was traditionally being taught to engineers. A comparison of the key features of perspective and traditional sketching skill is shown in Table 3.1. Perspective drawing's key contribution for engineering is it develops students' freehand sketching abilities by introducing techniques for better line quality of sketches and providing a framework that gives the ability to represent complex shapes. It also is focused on the sketching of products rather than scenes, human portraits, or other types of sketches. What is traditionally taught to engineers during the sketching portion of their course is exclusively isometric and orthographic views. Students learn how to view objects from different angles and piece together what the whole object would look like in their mind's eye. These exercises are usually completed with rigid objects and sketched on dot grid paper. The emphasis of this sketching is not line quality or sketch quality but rather the accuracy of the representation. The perspective sketching pedagogy adapted from industrial design provides an avenue to develop broader sketch skills and visual representation abilities. Two-point perspective is not the only sketching approach with these benefits, but it is known to be highly effective for quickly creating sketches of products, so it was chosen for this work. Perspective also allows the designer to show foreshortening and depth, which increases the realness of a drawing. This perspective sketching instruction has been deployed in engineering curriculums for several years (Hilton, Linsey, et al., 2018).

Table 3.1: Comparison of two-point perspective and traditional engineering sketching instruction

Perspective	Traditional
Freehand sketching, sometimes leveraging hand drawn or provided perspective guidelines	Often leverages graph/dot grid paper to create exact dimensions for projections
Realistic visual representation of everyday objects	Sometimes includes dimensioning of sketches
Explores objects from a variety of different views and angles	Exclusively isometric views and orthographic projections
Provides a framework building from 2D (lines, arcs, squares, circles, ellipses) to 3D primitives (cubes, cylinders, cones, spheres) to complex shapes	Simple 3D structures composed of straight lines and defined arcs
Emphasizes freehand “technique” for sketching such as drawing quick lines for smoothness and other tips for improving line quality	No Sketching techniques taught
Learn the basics of lighting and shading in sketches	No lighting or shading taught
Incorporates direct qualitative feedback on sketching form and line quality	No feedback on sketch quality, only feedback on accuracy

The demands of teaching freehand perspective sketching in a classroom are high. First, the instructor must be trained in technical perspective sketching skills, which most engineering instructors are not. Second, this type of skill is often taught in a studio-style class where the instructor can offer more one-on-one feedback. This type of individualized instruction is time-consuming and typically not possible in first-year engineering design and graphics courses due to their class size. To overcome this hurdle and offer more personalized instruction on a larger scale, an intelligent tutoring system called Sketchtivity was developed (Li, Hilton, Hammond, & Linsey, 2016; Williford et al., 2016). Sketchtivity leverages artificial intelligence (AI) and machine learning algorithms to offer personalized feedback to students. The platform provides instant feedback on each sketch, summative feedback at the end of each lesson, and suggestions on ways to improve throughout the process. Sketchtivity has been implemented at multiple universities and utilized by hundreds of students. It has been shown to improve students' sketching accuracy and speed (Keshavabhotla et al., 2017).

The goal of this chapter is to explore possible avenues for improving engineers' freehand sketching ability. This work culminates in three studies focused on the type of instruction, method of completing and providing feedback on assignments, and length of instruction. The first study is focused on the type of instruction students receive; this will be referred to as the *Perspective Study*. I compare the impacts of traditional sketching instruction and the adapted perspective sketching instruction in the engineering classroom by analyzing differences in sketch quality before and after instruction. This data was collected as the institution transitioned its curriculum from traditional to perspective sketching instruction. Previous results from this data showed that perspective sketching instruction was effective at improving students' spatial visualization skills (Hilton, Gamble, Li, Hammond, & Linsey, 2018; Hilton, Linsey, et al., 2018). Preliminary results of the impacts on sketching ability showed that perspective sketching significantly improves freehand sketching skills compared to traditional engineering sketching (Hilton et al., 2017). This chapter expands upon that work by revising and improving the evaluation techniques. The second study explores the implementation of the intelligent tutoring software, Sketchtivity; this will be referred to as the *Software Study*. I examine the impacts of the intelligent tutoring system on sketching improvement. Students receiving perspective sketching instruction are split into two groups and asked to complete their homework either on paper (control) or on Sketchtivity with a stylus and touchscreen (experimental). I compare the improvement of sketching skills and the drawing self-efficacy between the two groups. The software study has been implemented in three courses: an entry-level undergraduate engineering design course at two universities and a graduate engineering design course at one university. The third study explores the impacts of the length of instruction provided to students; this will be referred to as the *Instruction Length Study*. I analyze how much instruction is necessary to significantly improve freehand sketching skills. Existing courses vary in the amount of time dedicated to sketching instruction: between the two entry-level courses in the study, one spends five weeks on sketching while the other spends three. To better understand how much sketching instruction is necessary to improve students' sketching ability, I compare the improvements in freehand sketching skills between these two different length interventions. From these studies, this chapter addresses the following three research questions:

1. *To what extent does perspective sketching instruction improve freehand sketching skills?*

2. *To what extent does an intelligent tutoring system such as Sketchtivity improve freehand sketching skills?*

3. *To what extent do students enrolled in a class with 5-weeks of instruction in sketching have significantly higher freehand sketching skills and sketching self-efficacy than students enrolled in a course with 3-weeks of instruction?*

The questions posed here shed light on the benefits of freehand perspective sketching for engineering students. The differences in skill development between the two instruction types, traditional and perspective, will guide engineering educators in the future. Understanding the value of an intelligent tutoring software will help grant access to higher quality instruction to a greater number of students as more educators are encouraged to implement this type of tool in their courses. Lastly, exploring the differences in skill development between two lengths of sketching instruction will guide the amount of weight educators put on sketching education in the future.

3.1 Methods

This chapter presents results from three studies on improving sketching ability of engineering students through perspective sketching education. The three studies included in this chapter were collected from two universities. University A is a large technical university in the southeastern region of the United States. It is regarded as a top engineering university and has a strong industrial design program. University B is a large state university located in the south-central region of the United States and is also regarded as a top engineering university.

The perspective study compares the improvement of freehand sketching skills in students under traditional engineering sketching instruction and perspective sketching instruction. This study was conducted in an entry-level engineering design and graphics course at University A during the Fall 2015 and Spring 2016 semesters. The study was conducted in two sections of the course each semester taught by two different instructors – one teaching the traditional sketching method and one teaching the perspective sketching method in each semester. Before and after the sketching portion of the course, students completed a Sketching Foundations Test and two spatial visualization tests, the Revised Purdue Spatial Visualization Test and the Mental Rotations Test. The results of the two spatial visualization tests are published in previous work (Hilton, Linsey, et al., 2018). This chapter focuses on the results of the Sketching Foundations Test, which is a test of basic perspective sketching skills that will be described in full later in this section.

The software study compares the effectiveness of the Sketchtivity intelligent tutoring platform compared to perspective sketching assignments on paper. This study was conducted at Universities A & B in three courses during the Fall 2020 and Spring 2021 semesters. At University A, Sketchtivity was implemented in two out of seven sections of an undergraduate entry-level engineering design and graphics course in Spring 2021 and in the only section of a graduate engineering design course in Fall of 2020. The undergraduate course incorporated five weeks of sketching instruction, and the graduate design course incorporated two lectures on sketching instruction. At University B, Sketchtivity was implemented in one section of an undergraduate entry-level engineering graphics course in Fall 2020. University B's entry-level engineering graphics course incorporated three weeks of sketching instruction. In each of the three courses, students were split within the course and randomly assigned to one of the two conditions. Students in the experimental condition completed a portion of their homework on Sketchtivity, and students in the control condition completed all of their homework on paper. Students were evaluated before and after their sketching instruction with the Sketching Foundations Test and sketching self-efficacy survey.

The instruction in the courses led students through two-point perspective sketching techniques. First, students learn to draw a cube in two-point perspective. Within this lesson, students learn the correct form for drawing straight and accurate lines and scaling things in perspective. The cube then becomes a method of forming construction lines to draw other shapes. Students learn how to draw 3D primitives including cylinders, cones, and spheres, and then they advance to draw more complex forms which can be extrapolated to visually represent any shape. The lessons on Sketchtivity progressed through 3D primitives in two-point perspective. After that point, all assignments were completed on paper for both groups.

The instruction length study compares the improvement in freehand sketching ability and the increase in drawing self-efficacy between the two lengths of sketching instruction – 5 weeks and 3 weeks. For this study, I will compare the outcomes from the entry-level design and graphics courses at University A (5 weeks) and University B (3 weeks). Both courses were undergraduate entry-level engineering courses, both instructors taught from similar material on perspective sketching, and both courses implemented similar homework assignments. However, there are several differences in the instruction that should be noted. The two courses were taught by different instructors at different universities, which could lead to differences in student populations.

3.1.1 Sketchtivity

Sketchtivity is an intelligent tutoring software platform that offers dynamic, personalized feedback to students. Sketchtivity provides real-time feedback on sketch accuracy, smoothness, and speed. The platform offers instruction on basic 2D shapes such as lines, squares, circles, and ellipses and on 3D primitives in perspective such as cubes, cylinders, cones, and spheres. Instruction for each unit is preceded by a brief video lesson followed by sketching practice assignments with feedback. The videos were not assigned for the students to watch, and students generally do not watch them, as evidenced by their low view count relative to the class size. In each section, students are asked to complete eight sketches of the practice shape. An example of the cube exercise is shown in Figure 3.1. After each sketch, they are shown feedback on their accuracy. At the end of each section, students are provided summative feedback based on average measures of the eight practice sketches they just completed. The summative feedback breaks down into three categories shown in Figure 3.2: (1) Sketching metrics – the perspective sketching evaluation algorithm provides scores on sketching accuracy, smoothness, and speed. (2) Overall score – Sketchtivity provides an overall score displayed as a star rating out of five. This overall score is based on a function of the sketching metrics. (3) Suggestions for improvement – the algorithm uses the evaluation to make an educated suggestion for students to improve their sketching ability. For example, it will offer a suggestion like, "Great job! Try sketching a bit faster to improve precision and smoothness." The goal of the feedback scores is to motivate students to improve by challenging them to improve their scores.

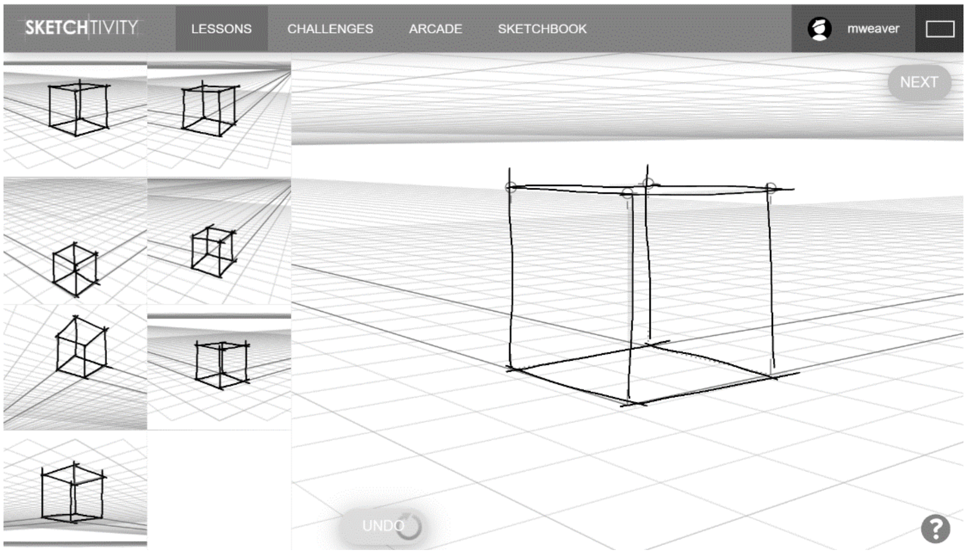


Figure 3.1: Sketchtivity interface – cube assignment

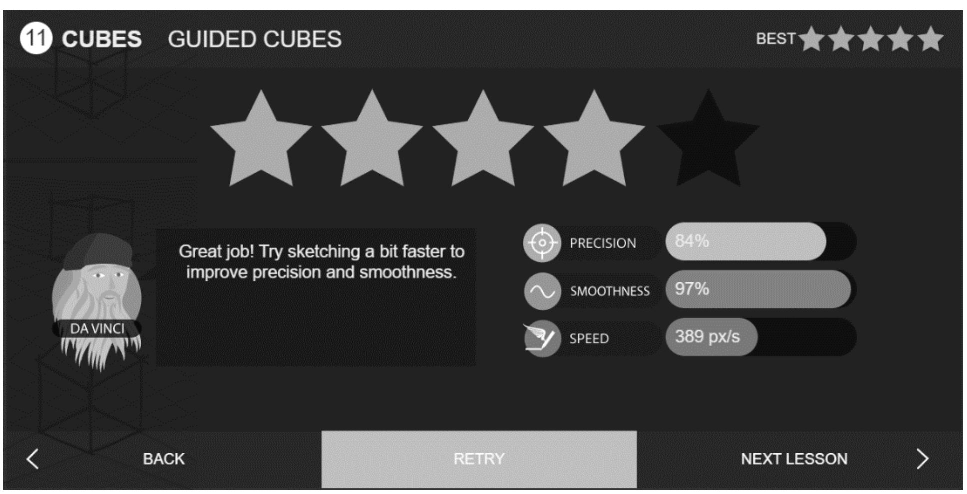


Figure 3.2: Sketchtivity interface – instructive feedback

3.1.2 Evaluation of Sketching skills

Students' sketching improvement in the course is evaluated using two tools: the Sketching Foundations Test and Drawing Self-Efficacy Instrument (DSEI) (Jaison et al., 2021 in press). The Sketching Foundations Test is a series of drawing tasks mostly consisting of primitive shapes in two-point perspective (shown in Appendix A). Participants are asked to sketch the following: horizontal straight lines, diagonal straight lines, squares, circles, ellipses, a cube, a cylinder, and a camera. The test provides guidelines or points where appropriate to guide the sketching task. In this chapter, I focus on the camera exercise. The camera exercise prompt is shown in Figure 3.3. The participants are given no time limit to complete the test, and they are instructed to complete the task freehand without the help of straight edges or gridlines. All Sketching Foundations Tests were completed on plain paper with no guidelines.

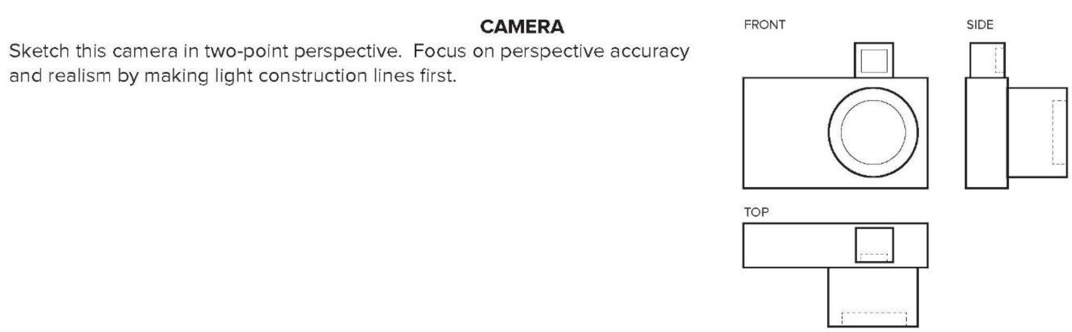


Figure 3.3: Sketching Foundations Test – camera prompt

The Sketching Foundations Test is evaluated by trained raters. Each rater independently evaluates each sketch for overall sketch quality on a five-point scale, with 1 being the lowest quality and 5 being the highest. Raters are instructed to use the whole scale in their ratings, with a score of 5 representing the highest quality sketch in a sample of ratings, not an absolute highest possible quality. Raters were instructed to look through many of the sketches before beginning the rating process to appropriately calibrate for the sample. For this study, raters were instructed to use their intuitive understanding of quality based on the prompt given. Each sketch was anonymized and presented to the raters in a random order, but the same random order was used in all cases. Therefore, raters were blind to the experimental condition of the participant, which university the participant was from, and whether the sketch was completed before or after the intervention. An example sketch is shown in Figure 3.4.

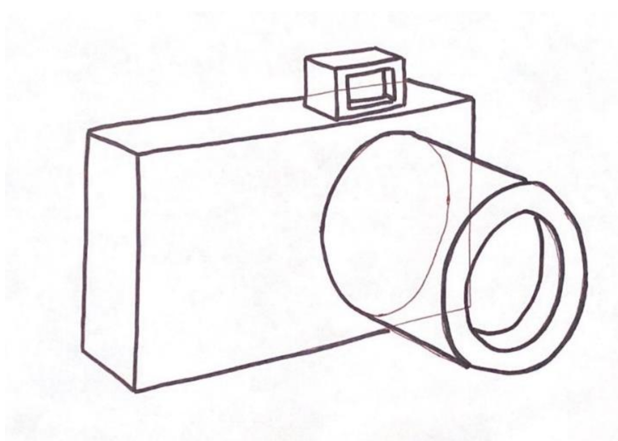


Figure 3.4: Sketch example – camera

The sketching evaluations in this chapter were completed by two raters: a mechanical engineering graduate student who received training in two-point perspective sketching through this project and an industrial design graduate student with extensive expertise in two-point perspective sketching techniques who had previously worked as a teaching assistant for a sketching course within the industrial design program. The two raters first evaluated a sample of sketches independently (n = 270). The initial agreement rating set had an intraclass correlation coefficient (ICC) of ICC = 0.803. The two raters met to discuss all of the major disagreements in rating. It became clear through discussion that one of the raters was systematically too high on some evaluations. The raters separated, and this rater reevaluated the data set independently. The new interrater agreement was ICC = 0.871. The raters then evaluated the remainder of the data set independently for a total of n = 505. The final interrater agreement on the full data set was ICC = 0.862. This shows good interrater agreement (Koo & Li, 2016). The intraclass correlation coefficient used assumed a two-way mixed effects, absolute agreement, and average measures (Koo & Li, 2016). Both raters evaluated all of the sketches in this study. Therefore, an average of their ratings was used for the analysis in this chapter.

3.1.3 Drawing Self-Efficacy Instrument

The Drawing Self-Efficacy Instrument is a validated survey tool consisting of 14 items (Jaison et al., 2021 in press). The instrument asks students to rate their confidence in different drawing situations on an 11-point scale. The instrument breaks down into three factors: self-efficacy with respect to drawing to solve problems and communicate, self-efficacy with respect to drawing specific objects, and self-efficacy with respect to drawing to create and express oneself. Students completed this survey as a part of the study before and after they received sketching instruction.

3.2 Results & Discussion

3.2.1 Perspective Study

RQ1: To what extent does perspective sketching instruction improve freehand sketching skills? The different sections of the first-year graphics course receiving two types of sketching instruction – traditional sketching and perspective sketching – were compared by analyzing the sketching skills of students before and after the instruction period, shown in Figure 3.5. Analysis was completed using a two-way, mixed-design ANOVA. Levene's test showed that the data did not violate the assumption of homogeneity of variance. A Shapiro-Wilk test showed that the data may not be normally distributed (Pre-test: $W = 0.960$, $p = 0.001$; Post-test: $W = 0.955$, $p = 0.001$). However, the normal probability plot appeared normal with all data falling on or near the line. An ANOVA was still chosen for the analysis because the omnibus test is robust to violations of normality (Glass, Peckham, & Sanders, 1972). Nonnormality has a "negligible effect" on the Type I error rate of the *F*-test (Harwell, Rubinstein, Hayes, & Olds, 1992, p. 333). The results of the ANOVA are displayed in Table 3.2. There was a significant main effect for the pre/post repeated measures factor, $F(1, 114) = 15.084$, $p < 0.001$, showing that overall, both groups improved from pre to post Sketching Foundations Test. However, there was a significant interaction effect between the pre/post factor and instruction type, $F(1, 114) = 6.069$, $p = 0.015$, showing that the groups did not change equally over the instruction period. Post hoc tests of simple main effects using the Bonferroni correction were conducted looking at the differences over pre to post within the two instruction type conditions. This showed that the perspective group significantly improved over the course of instruction $t(63) = 4.719$, $p < 0.001$, but the traditional group did not $t(51) = .962$, $p = 0.341$. The traditional group started at a much higher average sketch quality level than the perspective group but did not improve as dramatically. I am unsure why the traditional group started at a much higher sketching level than the perspective group. It is possible that there was a systematic preference among students for instructor or day of class, and this led to a systematic difference in initial sketching ability, or it is possible that it could just be random chance.

Table 3.2: ANOVA summary table for the perspective study

	df	*SS*	*MS*	*F*	*p*
Pre/Post	1	3.966	3.966	15.084	<0.001
Instruction Type	1	16.730	16.730	11.555	0.001
Pre/Post*Instruction Type	1	1.596	1.596	6.069	0.015
Error (Pre/Post)	114	29.976	0.263		
Error (Instruction Type)	114	165.058	1.448		

These data show that the perspective group improved significantly more than the students in the traditional group. The perspective instruction was effective at improving students' freehand sketching abilities. Teaching perspective sketching techniques has a positive effect on engineering education, equipping students with a powerful new skill for visual representation. Perspective sketching has many advantages over simple isometric representation. It allows the designer to show visual depth in their representation, enhancing the realness of the image. In the engineering context, in particular, perspective sketching greatly challenges freehand sketching abilities compared to what is traditionally taught in engineering education. Isometric representation is generally taught on dotted or grid paper. Freehand sketching skills are essential to represent an idea quickly and to represent complex forms. Perspective sketching in engineering enhances freehand sketching and visual representation abilities.

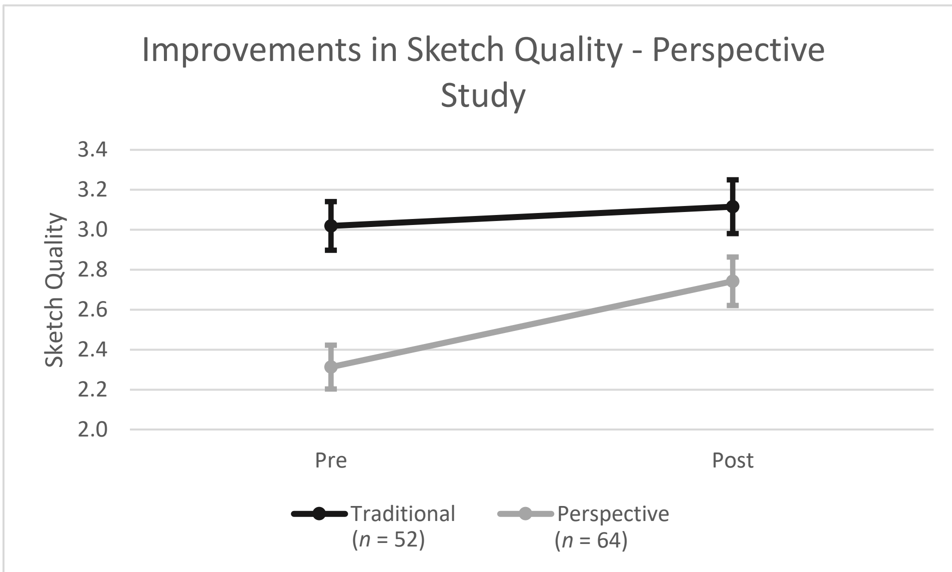


Figure 3.5: Differences in sketching improvements between traditional and perspective sketching instruction

3.2.2 Software Study

RQ2: To what extent does an intelligent tutoring system such as Sketchtivity improve freehand sketching skills? The experiment for this research question was implemented in three engineering courses, an undergraduate course at University A (n = 50), a graduate course at University A (n = 25), and an undergraduate course at University B (n = 59). Each course had a different instructor. In total, 134 students participated in the experiment – 53 students used Sketchtivity to complete some of their homework assignments, and 81 participated exclusively on paper as a control group. The analysis for this research question was completed using a three-factor mixed-design (or split-plot) ANOVA. Of the three factors, one is a within-subjects factor – pre/post, which represents the change pre to post over the instruction period – and two factors are between-subjects – course, to account for the different courses in which the study was conducted, and software condition represented as paper (control) or tablet group. The data showed homogeneity of variances according to Levene's test. However, a Shapiro-Wilk test showed a departure from normality (Pre-test: $W = 0.910$, $p < 0.001$; Post-test: $W = 0.943$, $p < 0.001$). This has a negligible effect on the Type I error rate of the F-test as noted above (Glass et al., 1972; Harwell et al., 1992). The changes in sketch quality scores in the three courses are shown in Figure 3.6, and the ANOVA summary table is shown in Table 3.3. The analyses showed that there was a significant main effect for the pre/post factor, $F(1, 129) = 15.551$, $p < 0.001$. However, this was mitigated by a significant interaction effect between pre/post and course $F(1, 129) = 67.959$, $p = 0.007$. No other interaction effects were statistically significant. Post hoc analysis of simple main effects with the Bonferroni correction showed that students significantly improved in sketch quality in the University A undergraduate course $t(50) = 5.073$, $p < 0.001$, but not in the University A, graduate course, $t(24) = 1.252$, $p = 0.223$ or the University B course, $t(58) = 0.173$, $p = 0.864$. The University A, undergraduate course had the longest sketching instruction intervention and had the largest effect on students' sketching skills. This speaks to the importance of the length of sketching instruction for students, which is explored more directly in the next section.

The lack of significant interaction effect with software condition shows that Sketchtivity did not have a significant impact on improving students' sketch quality. On visual inspection of Figure 3.6, we see that the tablet group using Sketchtivity did not significantly differ from the paper group. For the University A undergraduate course, the two groups started and finished at different average sketch quality scores. All students in all courses were randomly assigned to software conditions, so the difference was due to random chance. In the University A graduate course and at University B, we see that the tablet group trended towards more positive change. Both of these courses had much shorter sketching instruction periods than the University A undergraduate course. It could be that Sketchtivity has a higher impact on shorter sketching periods, and this will be explored in future work. However, at this point, I can only conclude that Sketchtivity did not significantly negatively impact students' abilities. As a reminder, students completed tests of sketching skills on paper, and the tablet group had to work some on paper and some on a touchscreen with a stylus. Therefore, likely Sketchtivity and practicing on tablets does not hinder the development of sketching ability on paper. Sketchtivity also reduced the workload of the course instructor by providing feedback directly to students in real-time. With Sketchtivity evaluating students' sketches as they complete tasks or assignments, the instructors do not have to go back and provide feedback on these assignments.

Table 3.3: ANOVA summary table of sketch quality analysis for the software study

	df	*SS*	*MS*	*F*	*p*
Pre/Post	1	6.179	6.179	15.551	<0.001
Software	1	0.366	0.366	0.226	0.635
Course	2	16.717	8.359	5.162	0.007
Pre/Post*Software	1	0.406	0.406	1.021	0.314
Pre/Post*Course	2	6.324	3.162	7.959	0.001
Software*Course	2	5.403	2.701	1.668	0.193
Pre/Post*Software*Course	2	0.266	0.133	0.335	0.716
Error (Pre/Post)	129	51.255	0.397		
Error (Between Subjects)	129	208.887	1.619		

There is also a concern in this study design about the level of influence Sketchtivity was allowed to have on students. Because this experiment was integrated into courses with existing curriculums, most of the existing paper assignments were retained in the curriculum. Therefore, the experimental assignments – the sketching practice completed on Sketchtivity and the equivalent practice completed on paper functioned more as supplementary sketching practice in some of the courses. This resulted in even the tablet group completing a great deal of their homework on paper. This essentially may have washed out the impacts of Sketchtivity on students sketching skills. Future work will attempt to more directly measure the impacts of the feedback provided by the Sketchtivity software. All students will complete a larger portion of their sketching homework on tablets and the feedback provided by Sketchtivity will be adjusted (removed or reduced) for groups of students without their knowledge.

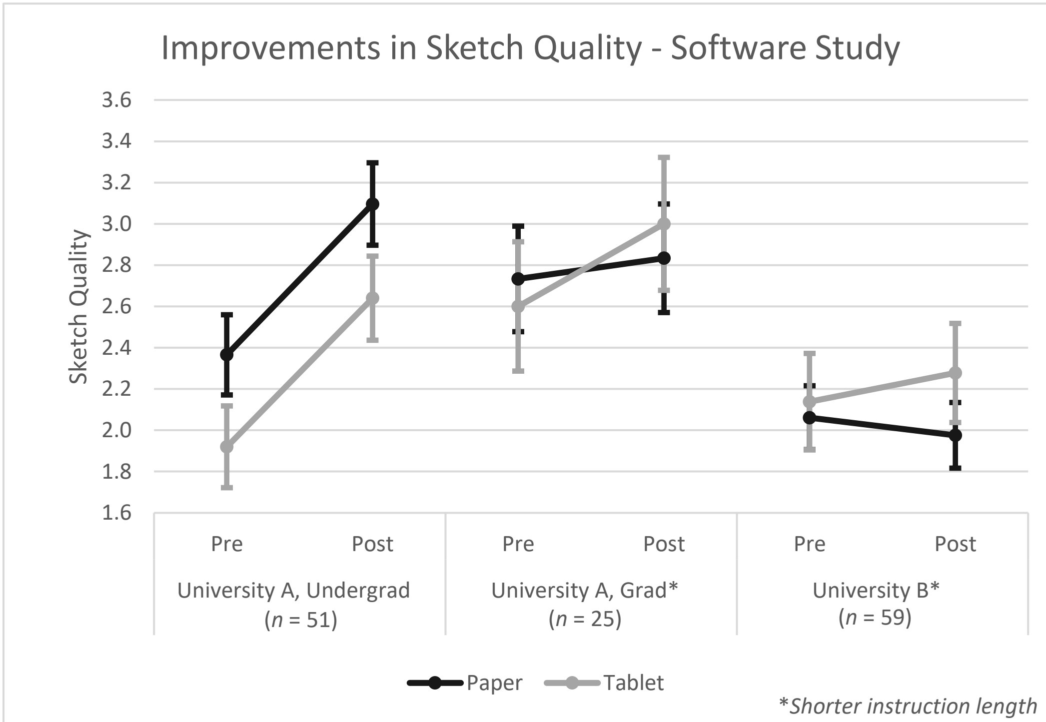


Figure 3.6: Improvements in sketch quality in three courses

I then analyzed the differences in the DSEI scores between the Sketchtivity and paper groups using a three-factor ANOVA displayed in Table 3.4. The DSEI data did not violate the assumption of normality by a Shapiro-Wilk test. However, Levene's test showed that the variances were not equal on the Post-instruction DSEI measure ($F = 2.485$, $p = 0.036$). However, the ratio of variances was low (< 2), which is only associated with a "modest inflation" of the Type I error rate of the F-test ($\alpha \approx 0.053$) (Harwell et al., 1992). Thus, an ANOVA was still used for the analysis. I found that there was a main effect for the pre/post factor $F(1, 115) = 91.954$, $p < 0.001$, showing that, on average, all individuals increased in drawing self-efficacy over the period of instruction. None of the interaction effects were significant. The increase in drawing self-efficacy score did not vary by course or by software condition. The improvement in drawing self-efficacy of the paper and tablet groups can be seen in Figure 3.7. Both increased similarly, and this trend was the same in all courses. Therefore, the use of Sketchtivity did not impact students' drawing self-efficacy significantly. DSEI increased meaningfully due to instruction alone.

Table 3.4: ANOVA summary table of DSEI analysis for the software study

	df	*SS*	*MS*	*F*	*p*
Pre/Post	1	89.204	89.204	91.954	<0.001
Software	1	3.215	3.215	0.677	0.412
Course	2	23.147	11.574	2.438	0.092
Pre/Post*Software	1	0.477	0.477	0.491	0.485
Pre/Post*Course	2	1.293	0.646	0.666	0.516
Software*Course	2	9.552	4.776	1.006	0.369
Pre/Post*Software*Course	2	1.832	0.916	0.944	0.392
Error (Pre/Post)	115	111.561	0.970		
Error (Between Subjects)	115	545.822	4.746		

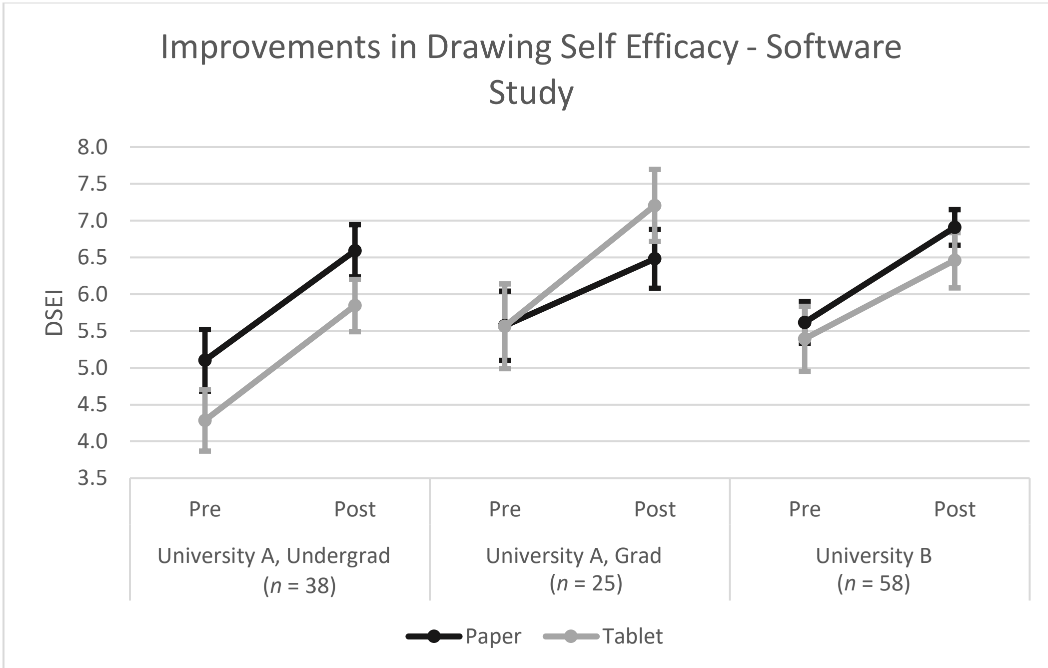


Figure 3.7: Similar changes in DSEI for paper and Sketchtivity experiment groups (error bars are +/- S.E.)

3.2.3 Instruction Length Study

RQ3: To what extent do students enrolled in a class with5-weeks of instruction in sketching have significantly higher freehand sketching skills and sketching self-efficacy than students enrolled in a course with 3-weeks of instruction? For the instruction length study, I compared both the Sketching Foundations Test ratings and the DSEI scores from the University A undergraduate course and the University B course. As a reminder, the two courses allotted five and three weeks to sketching instruction, respectively. Both courses are entry-level graphics courses using similar instruction material and similar homework assignments. Analysis was conducted using a two-factor mixed-design ANOVA. Levene's test showed that the variances were homogeneous. However, similar to the previous sketch quality scores, the Shapiro-Wilk test showed a departure from normality (Pre-test: W = 0.900, $p < 0.001$; Post-test: W = 0.930, $p < 0.001$). The results of the ANOVA are displayed in Figure 3.8, and the ANOVA summary table is displayed in Table 3.5. There was a significant main effect for the pre/post factor $F(1, 108) = 17.420$, $p < 0.001$, showing improvement between the two groups from pre-test to post-test. However, this was mitigated by a significant interaction effect between instruction length and pre/post $F(1, 108) = 19.127$, $p < 0.001$, showing that the length of instruction had a significant effect on how much students improved in sketch quality. Post hoc tests for simple main effects with the Bonferroni correction revealed that the 5-week group significantly improved, $t(50) = 5.073$, $p < 0.001$, while the 3-week instruction group did not, $t(58) = 0.173$, $p = 0.864$.

This can be clearly seen in Figure 3.8. The group that received the longer instruction length improved by an average of 0.7 on a five-point scale, and the shorter instruction length group showed no improvement on average. These data show that engineers need more than just 3 weeks of sketching instruction. The minimal instruction time results in minimal improvement in freehand sketching skills. To make matters worse, this lack of crucial sketching skills may indicate a lack of improvement in spatial visualization skills as well. Hilton et al. showed that most of the improvements in spatial visualization occurs during the sketching instruction portion of the course, not the CAD portion of the course that covered 3D solid modeling (Hilton, Linsey, et al., 2018), but Hilton et al., did not evaluate the impact of only the CAD. It is possible that CAD alone can improve spatial visualization. In short, minimizing sketching instruction to this degree could have repercussions beyond just affecting this skill.

For the instruction length study, there is a limitation of the context of the 3-week and 5-week instructional periods. The two courses were taught by different instructors at different institutions with different student populations. These are all factors adding noise to the study that could be contributing to the results. The University A undergraduate course and the University B course were chosen for comparison to control for as many factors as I could – similar instruction, similar assignments, and similarly aged students. However, in an ideal world, both conditions would be taught by the same instructor at the same university. Unfortunately, changes like this were not possible in the context of this study due to institutional curriculum practices. Future work will look to unify these conditions to make more accurate comparisons.

Table 3.5: ANOVA summary table of sketch quality analysis for the instruction length study

	df	*SS*	*MS*	*F*	*p*
Pre/Post	1	6.866	6.866	17.420	<0.001
Instruction Length	1	10.283	10.283	6.426	0.013
Pre/Post*Instruction Length	1	7.539	7.539	19.127	<0.001
Error (Pre/Post)	108	42.570	0.394		
Error (Instruction Length)	108	172.804	1.6		

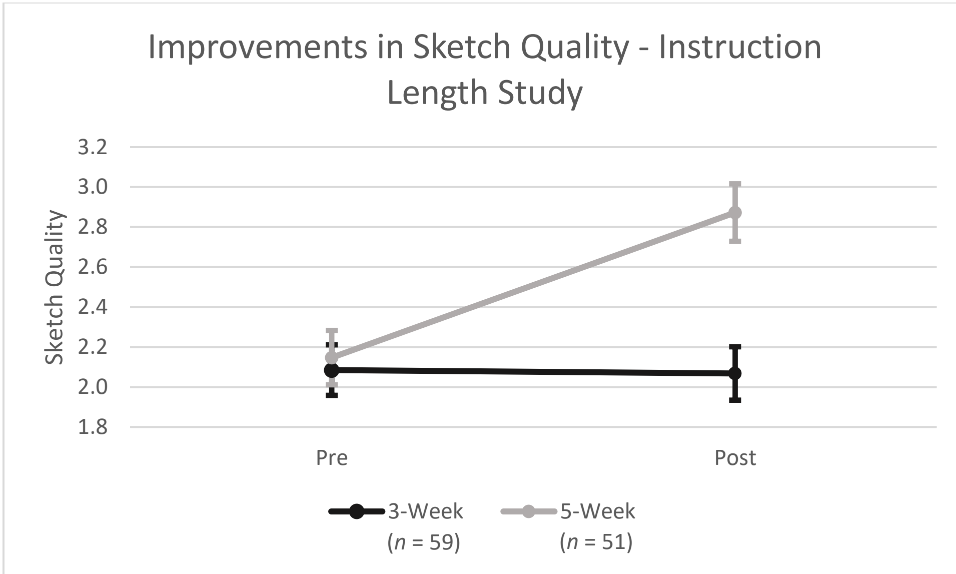


Figure 3.8: Differences in improvements in sketching skills between 3-week and 5-week instruction lengths

I found similar results to the software study with regards to the DSE displayed in Figure 3.9 and Table 3.6. Analysis was conducted using a two-factor mixed-design ANOVA. The DSEI data met the assumption for normality according to a Shapiro-Wilk test. However, the post-instruction DSEI data showed a violation of the homogeneity of variance assumption by Levene's test ($F = 4.418$, $p = 0.038$). The ratio of variances was again quite small (1.6), so this violation has very little effect on Type I error rate (Harwell et al., 1992). The ANOVA showed a significant main effect for pre/post $F(1, 94) = 89.337$, $p < 0.001$, showing that on average both groups significantly improved in DSEI scores. There were no significant differences in improvement between instruction length groups $F(1, 94) = 1.056$, $p = 0.307$. It is interesting that there is a difference in improvement in sketching ability while drawing self-efficacy changes are similar. These results beg the question of what caused the increase in confidence if the reason is not the increase in skill?

It could be that students feel more confident equipped with their new knowledge of sketching techniques, but they lack the practice with those sketching techniques to substantiate it. However, while shorter interventions may not improve sketching ability, improving confidence could likely lower their inhibition towards sketching in engineering design, which could increase their willingness to sketch in the design process. As more fluent sketching has been associated with positive design outcomes, this outcome is notably desirable for students as they develop their design skills in general.

Table 3.6: ANOVA summary table of DSEI analysis for the instruction length study

	df	*SS*	*MS*	*F*	*p*
Pre/Post	1	86.805	86.805	89.337	<0.001
Instruction Length	1	23.057	23.057	4.592	0.035
Pre/Post*Instruction Length	1	1.026	1.026	1.056	0.307
Error (Pre/Post)	94	91.336	0.972		
Error (Instruction Length)	94	472.035	5.022		

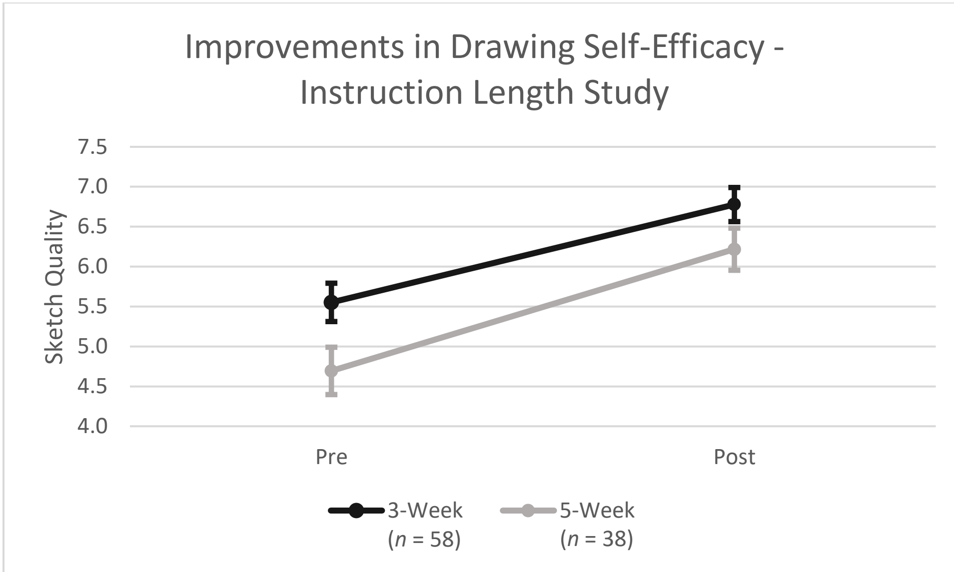


Figure 3.9: A 3-week instruction period is adequate for significantly increasing students' drawing self-efficacy (error bars are +/- S.E.)

3.3 Conclusion

Freehand sketching is a critical skill for engineering students to develop to improve their visual communication and spatial visualization skills. Improving spatial visualization skills through traditional engineering sketching instruction has been shown to positively impact retention, demonstrating the importance of these skills in the engineering curriculum (Sorby & Veurink, 2010). At the institutions in which we are collecting data, engineering curriculums are only limitedly teaching this critical skill, potentially hurting both student outcomes and retention. Naturally, a first step to address this issue is to improve sketching education within engineering curriculums. To determine the most effective techniques to teach sketching in engineering classrooms, this chapter looked at improving students' freehand sketching ability across three variables: instruction type, an

AI-based intelligent sketch tutoring platform such as Sketchtivity, and length of sketching instruction. It was shown that teaching students perspective sketching techniques significantly improved their freehand sketching skills, which equipped the students with a new and powerful tool for visualization. These freehand sketching skills are critical to relay visual information to design team members and externalize concepts quickly. In examining the impacts of Sketchtivity, it was shown that students practicing on tablets and paper improved their skill similarly. This at the very least means that practicing on a tablet did not hinder students' sketching skill development measured on paper evaluations. Future work will seek to specifically measure the impact of the feedback that Sketchtivity provides to gain clearer understanding of the impacts of the software on sketching skills.

It was also shown that students improved much more on average from 5 weeks of sketching instruction over 3 weeks. In fact, the students in the 3-week instruction group showed no statistically significant improvement on average. Due to instructor differences, these conclusions are limited. However, this speaks to the fact that sketching instruction is underprioritized in many engineering curriculums. Only a few weeks of sketching instruction might not influence students' sketching abilities at all, which in turn might limit the development of spatial visualization skills. Freehand sketching skills are critical for engineering design and spatial visualization skills are critical to success in engineering. Even a change from 3 weeks to 5 weeks of instruction can drastically change the impact on these skills. The authors believe this skill is worth the time investment. Lastly, it was shown that even a small amount of instruction can impact students' confidence in their sketching ability. This is crucial because increased confidence can help engineers draw more frequently in the design process. Sketching can benefit designers' thought processes and communication, therefore, removing barriers towards sketching should have positive outcomes on design processes. With these outcomes in mind, I believe engineering instructors should expand sketching instruction in their courses and leverage different sketching techniques such as two-point perspective to enhance students' freehand drawing abilities and better equip them for sketching in design.

CHAPTER 4. THE ROLE OF SKETCHING SKILLS AND SKETCH DETAIL IN IDEA GENERATION

Concept generation is the beginning of divergent exploration in the engineering design process. Concept generation plays a critical role in the design process as a whole. Ideation is an inexpensive and efficient means to find good solutions to problems, and it is important that it is thorough to give the best chances of a positive design outcome Ulrich and Eppinger (2011). Sketching plays an important role in being able to explore visual problems and solutions (Goldschmidt, 2014). There are many affordances of sketching that are inherently beneficial for design: it's fast and fluid, it requires minimal cognitive effort (with minor experience), it is tolerant of incompletion or inaccuracy, and it provides cues for further design development (Goldschmidt, 2014). These benefits make sketching a perfect (and free) tool to explore a visually challenging solution space. Fast and fluid visual representations are essential for communication in conceptual design enabling designers to quickly come to shared mental models (Goldschmidt, 2007). Sketches often inspire new or unexpected ideas from team members (Linsey et al., 2011; Shah et al., 2001). Lastly, empirical studies have shown that more frequent sketching in the design process correlates with positive design outcomes (Das & Yang, 2022; Song & Agogino, 2004; Yang, 2009). The strong benefits of sketching and the low bar for entry to sketch make it an essential tool for designers.

Given the many benefits of sketching for conceptual design, does it matter how well designers sketch? Anyone can pick up a pencil and paper and sketch a concept, but do all designers reap the same benefits from sketching regardless of their sketching skills?

There has been surprisingly little research examining the importance of sketching skills for engineers. Multiple studies have tracked students sketching during conceptual design using design logbooks and looked at relationships with sketching skills (Das & Yang, 2022; Yang & Cham, 2007). They found that sketching skills correlate positively with a higher frequency of sketching during conceptual design (Das & Yang, 2022; Yang & Cham, 2007). This correlation suggests that designers with better sketching skills were more inclined to sketch. An inclination for sketching is a positive factor given that design outcomes correlate positively with sketching frequency (Yang, 2009). Other studies looked at the importance of sketch quality for concept selection (Kudrowitz et al., 2012; Kwon & Kudrowitz, 2018, 2019). When intentionally manipulating the quality of product sketches, researchers found that participants' perception of concept creativity was influenced by the quality of the sketch (Kudrowitz et al., 2012). Similarly, people's perceptions of concept quality were also influenced by the quality of the sketch (Kwon & Kudrowitz, 2018, 2019). The relationship between perceived drawing quality and concept quality was strong with $r^2 = 0.50$ (Kwon & Kudrowitz, 2018). Sketch quality dominated participants' perception of concept quality. This is a startling effect size given the implications for design. A designer with stronger sketching skills could unintentionally commandeer a design project by simply putting in more time on a sketch for a concept. The strong relationship between sketch quality and concept quality emphasizes the importance of understanding the role of sketching skills in idea generation.

In this chapter, I present the results of an empirical study of sketching skills and ideation effectiveness. The study examined engineering students in an entry-level engineering design and graphics course. The first five weeks of the course instruction were focused on teaching two-point perspective sketching techniques. Students were asked to complete a test of sketching skills, generate sketched solutions for a design prompt, and complete a brief survey of drawing self-efficacy. Sketching skills were measured in two ways: on a paper test measuring sketch quality for perspective methods, and on a tablet test of sketching fundamentals. The tablet test was evaluated using the metrics from Sketchtivity, an online intelligent sketch-tutoring platform (Williford et al., 2016). Students completed the sketching evaluation tasks directly before and after the sketching instruction in the course. The focus of this study is to look at the relationship between independent measures of sketching skills and ideation effectiveness to better understand how participants sketching abilities are leveraged for idea generation. Examining students before after receiving instruction will shed light on how sketching skills and creative abilities improve from sketching instruction. The final piece of this study involves a revised set of measures designed to evaluate the content of the idea generation sketches.

4.1.1 Sketching Style

Several studies have laid out measures to evaluate the amount or type of information contained in a sketch. In a sense, these measures were intended to evaluate the elaboration of a sketch or amount of detail contained in the sketch. McGown, Green, and Rodgers (McGown et al., 1998) defined a measure of "sketch complexity" intended to evaluate sketches made by engineering students in a product design course. The scale defines five levels of complexity based on 2D vs. 3D form, shading, and annotation (McGown et al., 1998). This scale was later adapted by Song & Agogino (Song & Agogino, 2004) to include Shah et al.'s genealogical categorizations (Shah, Smith, & Vargas-Hernandez, 2003). Song & Agogino called their scale "level of detail" (Song & Agogino, 2004). The level of detail scale had five levels broken down similarly to McGown et al.'s scale. An abbreviated list of the Song & Agogino levels are listed below (Song & Agogino, 2004):

1. A line drawing that shows the physical principles, but no details to suggest product dimensions. May include labels. No other annotations. No dimensions.
2. A sketch or line drawing that shows the working principles, but no details to suggest product form. Line thickness varies to give emphasis. May have annotations.
3. A sketch or drawing that includes product form. May use rough shadings. May be annotated.
4. A sketch or drawing that shows product form with annotation. Some product features illustrated in detail. May include dimensions.
5. 3D form or multi-view 2D drawings to show the entire product form. Has dimensions and annotations.

Variations of the McGown et al. and Song and Agogino scales were also adopted in several other studies (Grenier & Schmidt, 2007; Ruocco, Westmoreland, & Schmidt, 2009; Westmoreland et al., 2011). I did not elect to adopt these scales in the current chapter for two reasons. First, the scales are double-barreled (or multi-barreled) in their evaluations – for example, the scale above asks to evaluate sketch views and annotation simultaneously. Double-barreled evaluations are detrimental because they attempt to measure multiple things at once clouding which variable is actually being assessed (DeVellis & Thorpe, 2021). Second, the McGown sketch complexity measure (McGown et al., 1998) is not a good fit for the context of an idea generation study. The top three levels of the scale describe sketches that involve heavy shading and color to suggest detailed forms. Sketches at that level of detail are not productive for short idea generation sessions, so most of the concepts in our study would have only registered on level 1 or 2. Therefore, I sought to reframe these measures to address the shortcomings for our context.

Using sketch complexity and level of detail as a reference, the relevant components were broken down into their separate pieces that applied to the context of the current study. Then the data were examined with these components in mind to determine if all of the components were mutually exclusive and represented a collectively exhaustive framework for the sketch data in the current study. This resulted in a set of four measures:

1. Representation – the dimensions included in the form (2D, mix of 2D & 3D, or 3D)
2. Word Count – the number of words used to describe the concept
3. View Count – the number of views used to describe the concept
4. Texture/Shading – the use of texture, shading, hatching, or color to add detail to a sketch

In this dissertation, these four measures will be referred to as *sketch detail*. The sketch detail measures are used to evaluate the sketches produced during the idea generation activity. Having separate measures accounts for the double-barreled problems with previous measures, and, therefore, should provide more detailed information about the role of sketch detail in design.

4.1.2 Research Questions and Hypotheses

The relationship between sketching skills and ideation effectiveness is critical to understand to gauge the importance of sketching to the modern-day engineer. Sketching is only taught limitedly in some engineering programs (Linsey et al., 2011; Taborda et al., 2012; Weaver, Ray, et al., 2022; Yang & Cham, 2007), and understanding the significance of sketching skills in the design process could help prioritize this skill in engineering education. Sketch detail and drawing self-efficacy should provide additional understanding for this critical relationship. The research focus of this chapter is guided by the following goals.

Firstly, I am interested in the direct impact of sketching skills and drawing self-efficacy on ideation effectiveness. How skilled and confident designers are in their sketching abilities should predict their sketching frequency during ideation. Secondly, sketch detail should shed additional light on the nature of the relationship of sketching and idea generation. The purpose of sketch detail is to act as a mediating variable between sketching skills and idea generation abilities (shown in Figure 4.1). It is likely that sketching skills influence sketch detail, which in turn influences ideation effectiveness. Lastly, this chapter investigates the degree to which all of these constructs improve over the course of sketching instruction in an entry-level engineering design and graphics course. Studying changes in sketching skills, self-efficacy, and ideation effectiveness will give greater understanding of the broader impacts of developing sketching skills.

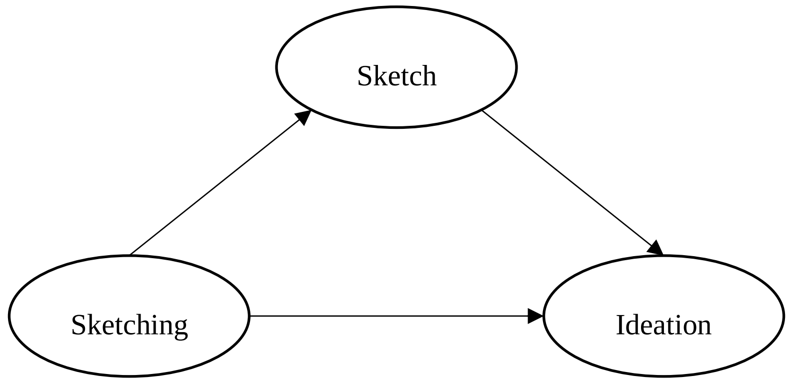


Figure 4.1: Hypothetical structural model of the relationship between sketching skills, sketch detail, and ideation effectiveness

With the aforementioned goals in mind, this chapter is guided by the following research questions.

RQ1. *To what extent do sketching skills and drawing self-efficacy predict ideation effectiveness?*

RQ2. *To what extent does sketch detail mediate the relationship between sketching skills and ideation effectiveness?*

RQ3. *To what extent does perspective sketching instruction improve sketching skills, drawing self-efficacy, sketch detail, and ideation effectiveness for entry-level engineering students?*

The first research question concerns the direct relationships of sketching skills and drawing self-efficacy predicting ideation effectiveness. I anticipate a positive relationship between sketching skills and ideation effectiveness because previous research has shown a positive correlation between sketching skills and sketching frequency during conceptual design (Yang & Cham, 2007). I hypothesize a similar relationship for drawing self-efficacy and ideation effectiveness – the more confident designers are the more fluent their ideation sketching may be. Our hypothesis for RQ1 is listed below.

H1a: Sketching skills will have a positive correlation with ideation effectiveness.

H1b: Drawing self-efficacy will have a positive correlation with ideation effectiveness.

The second research question concerns the mediation effect of sketch detail on the sketching skills and idea generation relationship. Mediation occurs when part or all of the influence of an independent variable on the dependent variable can be explained by an intermediary variable. For the relationship in this chapter, I hypothesize that sketching skills will predict sketch detail in idea generation, and in turn sketch detail will predict changes in ideation effectiveness (as shown in Figure 4.1). This mediating relationship results in sketching skills having a direct and indirect effect on ideation effectiveness. For the mediation relationship, I hypothesize a positive relationship between sketching skills and sketch detail – individuals with stronger sketching skills may be more inclined to draw at a higher level of representation, use texture/shading more often, and use more views to represent ideas. In short, we hypothesize that participants with stronger sketching skills will leverage their skills for more detailed sketched representations. We also hypothesize that word count will have a negative relationship with sketching skills and the other sketch detail measures. A designer with stronger sketching skills will likely leverage words less frequently to explain their concept, and vice versa a designer with poor sketching skills/confidence may rely more on words to explain their concept. The other half of the mediation relationship concerns sketch detail predicting ideation effectiveness. Previous research has shown that elaboration (measured as word count in text-based idea generation) negatively correlated with number of ideas generated (Dippo & Kudrowitz, 2015). Designers that produce more detailed representations may expend more resources and generate fewer concepts. Therefore, we hypothesize a negative relationship between sketch detail and ideation effectiveness. These prior results lead to the following hypotheses for research question 2.

H2a: Sketching skills will have a positive correlation with sketch detail resulting in higher level representation (3D instead of 2D), more texture/shading, higher view count, and lower word count.

H2b: Sketch detail will have a negative correlation with ideation effectiveness.

The final research question concerns the change in sketching and ideation measures over the course of sketching instruction. Previous research has shown increases in sketching skills and drawing self-efficacy over the course of similar length and type of sketching instruction (Weaver, Ray, et al., 2022). We anticipate that these increases in sketching skills and self-efficacy will lead to improvements in sketch detail and idea generation as well.

H3: Sketching instruction has a positive effect on sketching skills, drawing self-efficacy, sketch detail, and ideation effectiveness.

4.2 Methods

During the first week of the semester, before any sketching instruction occurred, students were evaluated on sketching skills, idea generation, and drawing self-efficacy.

Students were then evaluated again five weeks later on the same measures after receiving sketching instruction. The five weeks of sketching instruction is focused on two-point perspective sketching techniques derived from the sketching curriculum typically taught in industrial design (Hilton, Linsey, et al., 2018; Weaver, Ray, et al., 2022). For this study, we will look at between-subjects regressions between the sketching and idea generation measures, and we will look at within-subject improvements over the sketching instruction.

For the idea generation, two separate design prompts were used before and after the sketching instruction. The two prompts were the peanut sheller design prompt and the corn shucker design prompt (shown in (Levy, Hilton, Tomko, & Linsey, 2017; Weaver, Buck, et al., 2022)). These two problems have been shown to produce similar quantity scores (Levy et al., 2017). A two-by-two partial Latin square design was used to split participants between the two prompts. Participants were randomly assigned to a design prompt and grouped by course section to prevent crosstalk about the prompt. About half of the students were assigned to each design prompt before and after sketching instruction.

4.2.1 Participants

100 participants were included in the study for analysis. Originally 166 students participated in the study at least partially. Students were excluded from the final analyses if they did not complete all components of the study. Participants were also asked about their level of effort on the sketching and idea generation tasks. Participants were only asked after the second data collection to avoid influencing their effort during the second data collection. Participants were asked if they "tried their hardest", put in "moderate" effort, put in "minimal" effort, or if they "did not care" about the task. Participants who responded

that they put in minimal effort or did not care were excluded from the analysis. 24 students were excluded because of reporting minimal effort, and 42 were excluded for not completing all components of the study.

Of the 100 students included in the analysis, their ages ranged from 18 to 24. The vast majority of students were first-year engineering students, almost all students were majoring in aerospace or mechanical engineering, and there were 64 male students, 27 female, 2 gender fluid/non-binary, and 7 preferred not to disclose.

4.2.2 Sampling Procedures

Data were collected in an entry-level engineering design and graphics course. The course meets three times weekly with two one-hour lectures, and one three-hour lab. Data were collected during the lab portion of the course. Data were collected before and after the sketching instruction portion of the course. The pre-sketching instruction data were collected during the first week of the Spring 2022 academic semester, and the post-sketching instruction data were collected in the fifth week of the semester. The pre and post data collection followed the same procedure. Students first completed the idea generation portion followed by the sketching test, which was completed half on paper and half on tablet. For the tablet portion, participants were supplied with Microsoft Surface Go 2s with smart pens. Students would create an account at www.persketchtivity.com and the sketching test would automatically load. Lastly, they would complete a brief survey that included the drawing self-efficacy survey and questions on demographics. The idea generation task was timed – participants were given 2 minutes to review the problem and then 45 minutes to generate solutions. Students were allowed to complete the remaining activities in their own time. During the idea generation activity, students were not allowed to talk or work on other tasks. A graduate student was present to monitor and guide data collection. When students finished, they were allowed to work on other things or leave the lab. Students were offered extra credit in the entry-level course for participating in the study. The experiment protocol was approved for exempt review by the institutional review board.

4.2.3 Measures

This study involves four categories of measures (Figure 4.2): sketching skills, drawing self-efficacy, ideation effectiveness, and sketch detail. The following sub-sections describe evaluation and reliability for all of the listed measures.

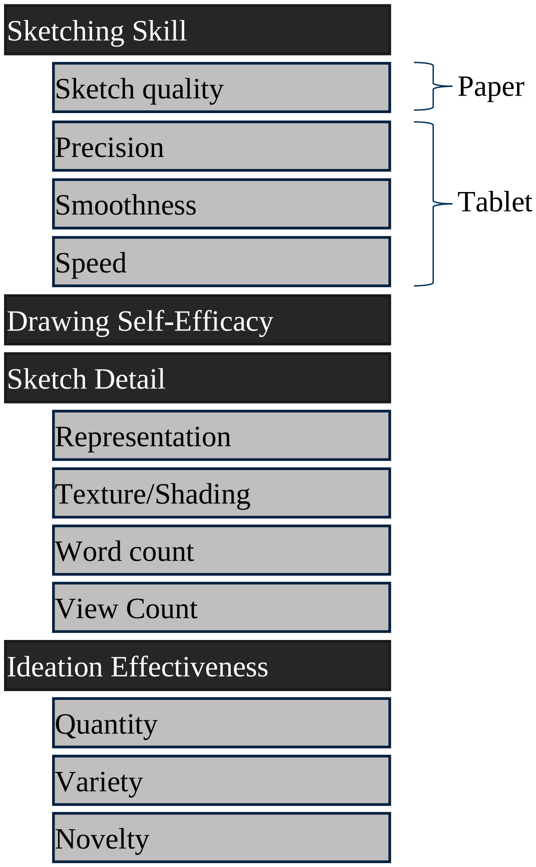


Figure 4.2: List of all sub-measures evaluated for constructs sketching skills, drawing self-efficacy, sketch detail, and ideation effectiveness

4.2.3.1 Sketching Skills

Sketching skills were measured through the Sketching Foundations Test. The Sketching Foundations Test is a test of basic sketching skills associated with perspective sketching (E. C. Hilton et al., 2016). The test has 8 sheets of sketching exercises ranging from lines to circles to a camera sketch that is a combination of 3D primitives. For this study, the test was broken down into two components: the 2D sketching basics (lines, squares, ellipses, etc.) were completed on a tablet, and the 3D shapes (cube, cylinder, and camera) were completed on paper.

The portion of the test completed on tablet was evaluated by Sketchtivity, an intelligent sketch tutoring software. Sketchtivity evaluates sketching skills on three measures: *precision*, *smoothness*, and *speed*. The tablet portion of the Sketching Foundations Test is comprised of five sheets each with different 2D drawing tasks: horizontal lines, diagonal lines, squares, circles, and ellipses. Each sheet has between 5 and 7 exercises on it corresponding to the drawing tasks. This allows an average to be taken of sketching ability instead of a single point. The data from Sketchtivity had to be cleaned to account for errors in calculations. For example, if there was a stray mark on the page the software would evaluate that as part of the sketch causing the scores to be wildly skewed. Scores with such errors were not representative of a participant's actual skill level and were therefore excluded. A graduate student in mechanical engineering went through each measure for each sheet and examined sketches to set a threshold for acceptable values for each measure. This resulted in missing data for some participants. We were able to account for some missing values by taking an average of scores for the data that was present. However, if a participant had less than three exercises remaining on any given sheet their data were not included in the analysis. On the pre-test, 72 participants had complete data for Sketchtivity, and on the post-test, 73 participants had complete Sketchtivity data. An average of the precision, smoothness, and speed scores were taken across the 5 sheets of the test for final Sketchtivity sketching skills scores.

The paper portion of the test was evaluated by human raters. Each of the sheets were evaluated for overall sketch quality by two raters: a graduate student in industrial design and a graduate student in mechanical engineering with training in two-point perspective sketching techniques. Both raters evaluated all participant sketches for this study. The inter-rater reliability (IRR) for the two rater's was $\alpha = 0.67$ (Krippendorff's alpha (Krippendorff, 2011)), which shows substantial agreement (Landis & Koch, 1977). An average of both raters' evaluations was taken for the score for each sheet. Then the scores for each sheet were summed for the final sketch skills score.

4.2.3.2 Drawing Self-Efficacy Instrument

Researchers have studied the validity of the Drawing Self-Efficacy Instrument (DSEI) through exploratory factor analysis (Jaison et al., 2021). The DSEI consists of 13 items that ask about participants confidence in their abilities for a variety of sketching tasks (Jaison et al., 2021). Participants respond on a scale of 0 to 10 for each of the items. All 13 items were averaged for each participant's DSEI score.

4.2.3.3 Sketch Detail

Sketch detail is comprised of four measures used to evaluate the idea generation sketches: representation, word count, view count, and texture/shading.

Representation is defined as the dimensions used to sketch form (2D or 3D). Representation was rated on a scale from 0 to 3 shown in Table 4.1.A 3 was given if the participant included a 3D view of the entire concept. Even if there are additional views drawn in 2D (e.g., a cross-section view), the solution was given a 3 for representation because they used a full 3D representation. Two raters, a professor of mechanical engineering and a graduate student in mechanical engineering, evaluated 10% of the data. IRR was calculated using Krippendorff's alpha and was found to be substantial ($\alpha = 0.74$). The full data was evaluated by a mechanical engineering graduate student. An average of representation scores across each participants ideas was used to as their representation score.

Table 4.1: Representation rating scale

Rating	Definition
0	Words only
1	Sketch is entirely 2D
2	Sketch uses 2D and 3D in a single sketch view
3	Concept includes an entire 3D sketch of a concept

Texture/shading was defined as the amount of texture, hatching, shading, and coloring used on each solution sketch. Texture/shading was rated on a scale of 0-3: 0 – words only; 1 – no texture/shading, only outlines of shapes; 2 – minimal texture, usually just hatching on 1 or 2 shapes; 3 – significant texture on many shapes, or shading used to suggest depth. Two raters, an undergraduate and graduate mechanical engineering student evaluated 10% of the data to check IRR. There was substantial agreement using Krippendorff's alpha between the raters ($\alpha = 0.62$). The full data set was evaluated by a mechanical engineering graduate student. An average of texture/shading on each participant's solutions was taken as their texture/shading score.

Word count was evaluated as the number of words on the page. Word count was evaluated manually by a graduate mechanical engineering student. All words on the page were counted regardless of whether they were labels, descriptions, or evaluations of the concept. In theory, there could be differences in behavior for different types of words on the page while sketching concepts. For example, participants may label everything out of habit or because prompted, but writing out detailed descriptions of products may indicate a different behavior and associated cognitive process. For this study a count of all words was used have a measure that is simple to interpret and simple to measure. This circumvents the need to categorize words into different purposes (e.g., labels, descriptions, process, etc.), but future work could examine types of language used during ideation to understand behaviors. An average of word count was taken across each participants ideas as their word count score.

View count was evaluated as the number of repeated views of a component on a page. Separate views included isometric/perspective views, orthographic, section views, process views, and detail views. A separate view was only counted if it was a repeated sketch of a component to provide additional information. If a solution's components were simply drawn separated this would only count as a single view. Two raters, an undergraduate and graduate student in mechanical engineering evaluated 10% of the ideas to check IRR. A Pearson correlation showed strong agreement between the two raters ($r = 0.90, p < 0.001$). The full data set was evaluated by a mechanical engineering graduate student. An average view count was taken across each participant's solutions as their view count score.

4.2.3.4 Ideation Effectiveness

For the idea generation task, participants were given 45 min to generate solutions to the given design prompts. 45 min was used as the ideation time based on previous research (Tsenn, Atilola, McAdams, & Linsey, 2014). Participants were given a packet of papers with a cover sheet, the design prompt, and 15 blank pages. Participants were asked to sketch on idea per page and annotate their ides to make them clear. Participants were allowed to use a pen or pencil, and participants could ask for more sheets of paper if they ran out.

Idea generation was evaluated using adapted versions of Shah et al.'s metrics for ideation effectiveness (Shah et al., 2003): quantity, variety, and novelty. The measures have been adapted for improved reliability (Linsey et al., 2011). Quantity was evaluated in a more detailed way applying the functional basis to count the number of non-redundant ideas on all sheets (Hirtz, Stone, McAdams, Szykman, & Wood, 2002; Linsey et al., 2011). A mechanical engineering undergraduate and a mechanical engineering graduate student both evaluated 10% of the data to check IRR for quantity. There was a 78% agreement between ideas rated and the scores for quantity from the two raters correlated with $r = 0.89$, which shows strong agreement. The whole dataset was evaluated by the mechanical engineering graduate student. The evaluation order was randomized to keep the evaluator blind to the participants identity and condition.

Variety and novelty are evaluated using a set of categories (or "bins") to sort the concepts into. Concepts are sorted into bins with similar ideas, and new bins are added if an idea significantly differs from all of the existing bins. Two participants, a mechanical engineering undergraduate student and a mechanical engineering graduate student rated 10% of the data for bins and had an agreement of $Cohen's\, \kappa = 0.65$, which shows substantial agreement. The full set of data was evaluated for bins by a mechanical engineering graduate student.

Variety is a measure of the breadth of solution space covered by a participants idea generation. Variety is calculating by counting the number of unique bins a participants solution set covers then dividing by the total number of bins. This ends up being a percentage of solution space covered for the final score. Novelty is the rarity or uniqueness of an idea. For novelty, the number of concepts in each bin is counted, and each bin receives a novelty score. The novelty score for each bin is calculated as one minus the frequency of that bin over the frequency of all bins. This gives an infrequency score – the more common an idea is the lower the novelty score. Each participant's novelty is calculated as a count of "novel" ideas. For this study, a threshold of 25% was set for a novel idea. Therefore, each idea a participant generates that was in the rarest 25% of ideas counts as a novel idea for their score. Novel-idea-count is a better measure than average novelty because average novelty can punish a participant for coming up with many common ideas even if they generate many uncommon as well (Reinig, Briggs, & Nunamaker, 2007).

The final measure for ideation effectiveness is quality, usually measured as the average quality of ideas or good-idea-count. Previous work showed that industry professionals' ratings of sketch quality and concept quality were strongly correlated ($r^2 = 0.50$) (Kwon & Kudrowitz, 2018). Sketch quality has a strong impact on how concepts are perceived (Kudrowitz et al., 2012). The strong effect size of the relationship between these measures would likely impact the results of the current study. If quality was examined, there would be no way to decipher whether the relationship between sketching skill and concept quality was due to the skill and creativity of the designers or the skewed perceptions of the raters. Therefore, we have decided to exclude this measure from the current study.

4.3 Results & Discussion

4.3.1 *Correlations*

RQ1. To what extent do sketching skills and drawing self-efficacy predict ideation effectiveness?

First, we looked at correlations between all measures in the study. These correlations show the simple bivariate, linear relationships between all measures revealing direct relationships within and between constructs. Correlation tables for all variables are shown for pre-sketching instruction and post-sketching instruction in Table 4.2 and Table 4.3, respectively. The following discussions first examine results within constructs to understand the relationships of the different sub-variables to one another. These within construct relationships are critical to understand the makeup of sketching skills and how the different aspects of sketch detail relate to one another. Then, we discuss the between construct relationships to answer the research questions.

For sketching skill, we examined the relationships between sketch quality, precision, smoothness, and speed. The sketching skills measures were very limitedly related. Only smoothness was consistently significantly related to overall sketch quality. Overall sketch quality had a moderate positive correlation with smoothness on both the pre ($r^2 = 0.20$) and post ($r^2 = 0.20$) tests. Precision showed a weak correlation with sketch quality on the pretest ($r^2 = 0.06$). Speed was not significantly related to sketch quality but was negatively correlated with precision ($r^2 = 0.11$) and positively correlated with smoothness ($r^2 = 0.21$) on the posttest. Sketching at higher speeds is important because it results in smoother lines for more experienced sketchers.

Table 4.2: Pre-sketching instruction Pearson correlations between all measures

Variable	Sketch Quality	Precision	Smooth-ness	Speed	DSEI	Repre-sentation	Texture/ Shading	Word Count	View Count	Quantity	Variety
Sketch Quality	-										
Precision	0.25*	-									
Smoothness	0.44**	0.21	-								
Speed	-0.09	-0.18	0.22	-							
DSEI	0.36**	0.11	0.08	0.10	-						
Representation	0.38**	0.01	0.24*	0.00	0.24*	-					
Texture/Shading	0.00	-0.14	-0.01	-0.10	-0.02	0.19	-				
Word Count	0.12	-0.09	0.03	-0.02	-0.13	0.01	0.05	-			
View Count	0.13	-0.02	0.06	0.05	0.03	0.00	0.08	0.48**	-		
Quantity	0.10	0.16	0.04	0.13	0.19	-0.10	-0.07	-0.25*	-0.22*	-	
Variety	0.13	-0.02	0.06	0.13	0.16	-0.08	-0.12	-0.39**	-0.20*	0.54**	-
Novelty	0.09	0.00	-0.10	0.06	0.07	-0.01	-0.06	-0.21*	-0.14	0.43**	0.73**

* $p < 0.05$, ** $p < 0.01$; $n = 72$ for correlations with precision, smoothness, and speed; $n = 100$ for all other correlations

Table 4.3: Post-sketching instruction Pearson correlations between all measures

Variable	Sketch Quality	Precision	Smooth-ness	Speed	DSEI	Repre-sentation	Texture/ Shading	Word Count	View Count	Quantity	Variety
Sketch Quality	-										
Precision	0.18	-									
Smoothness	0.44**	0.01	-								
Speed	0.08	-0.33**	0.46**	-							
DSEI	0.17	0.03	0.24*	0.18	-						
Representation	0.30**	0.15	0.14	0.28*	0.08	-					
Texture/Shading	0.09	0.08	0.17	0.09	0.08	0.27**	-				
Word Count	-0.12	-0.10	-0.03	0.13	0.05	-0.08	0.02	-			
View Count	-0.16	-0.20	-0.19	-0.05	-0.03	-0.18	0.16	0.49*	-		
Quantity	0.22*	0.20	0.23	0.15	0.17	0.01	-0.08	-0.22*	-0.28**	-	
Variety	0.15	0.33**	0.11	0.11	0.09	-0.01	-0.03	-0.32**	-0.33**	0.69**	-
Novelty	0.05	0.32**	0.08	-0.02	0.09	-0.10	-0.05	-0.24*	-0.29**	0.55**	0.75**

* $p < 0.05$, ** $p < 0.01$; $n = 73$ for correlations with precision, smoothness, and speed; $n = 100$ for all other correlations

Correlations between the sketch detail measures reveal relationships between representation, texture/shading, word count, and view count. For the most part these measures were largely independent. Previously, sketch detail (or level of detail (Song & Agogino, 2004)) was measured as a single variable with several factors convoluted together. These factors being largely independent suggests that they are measuring different things and should be evaluated separately. The two measures that were significantly associated were word count and view count. These two measures had a moderate positive relationship, which was of similar strength on the pre- ($r^2 = 0.23$) and posttests ($r^2 = 0.24$). Originally, we hypothesized that designers would either lean more on sketching (higher view count) or text (higher word count) to convey their concepts and that these two measures might be at odds with one another. However, it seems that both are driven by a similar construct, elaboration – the degree to which a designer expands upon and details their design solution (Dippo & Kudrowitz, 2015).

Next, we looked at correlations between the dependent variables – the ideation effectiveness measures to understand how quantity, novelty, and variety related to one another. There were moderate to strong correlations between all three measures. As quantity increases, novelty and variety are also more likely to increase. Originally, these metrics were intended to be evaluated separately as they were in theory evaluating separate constructs (Shah et al., 2003). However, in practice, they are highly correlated suggesting that number of ideas (quantity) is a large driving factor. The more ideas an individual generates generally leads to more solution space covered and discovery of more novel solutions (Kudrowitz & Dippo, 2013).

Lastly, we examined correlations between the predictor variables – sketching skills and drawing self-efficacy – and the dependent variables. Prior to sketch instruction, there were no significant relationships between ideation effectiveness and either sketching skills or drawing self-efficacy. On the posttest, sketching skills showed a weak correlation with idea quantity ($r^2 = 0.05$). Also on the posttest, precision was positively correlated to both variety ($r^2 = 0.11$) and novelty ($r^2 = 0.10$).

H1: Sketching skills and drawing self-efficacy will have a positive correlation with ideation effectiveness. Hypothesis 1 is partially confirmed. Sketching skills were independent of ideation effectiveness on the pre-test but showed a weak positive correlation with ideation effectiveness on the post-test. Overall sketch quality was correlated with quantity, and precision was correlated with variety and novelty. This mild relationship shows that after receiving sketching instruction, designers with higher sketching skills are more inclined to sketch more during idea generation. However, the effect size is very small.

RQ2. To what extent does sketch detail mediate the relationship between sketching skills and ideation effectiveness? Next, the mediating effects of the sketch detail measures were examined. First, correlations were analyzed between the constructs of interest. Then, Structural Equation Modeling (SEM) was leveraged to better understand the interactions of the variables and the overall fit of the mediation model.

Mediation modeled in Figure 4.1 involves a relationship between sketching skills and sketch detail, and then a relationship between sketch detail and ideation effectiveness. Of the sketch detail measures, sketching skills only had a positive correlation with representation (pre: $r^2 = 0.15$; post: $r^2 = 0.09$). Participants with higher sketch quality were more likely to draw in 3 dimensions but no more or less likely to write more words, sketch more views, or implement texture/shading during idea generation.

H2a: Sketching skills will have a positive correlation with sketch detail resulting in higher level representation (3D instead of 2D), more texture/shading, higher view count, and lower word count. Hypothesis 2a is partially confirmed. Sketching skills were positively correlated with representation but were independent of all other sketch detail measures. This is an interesting finding and suggests that sketching skills enable or encourage students to express ideas in more complex ways. Being opened up to the possibility of 3D over 2D sketches may open up new ways to represent ideas that could hopefully spur on creativity.

H2b: Sketch detail will have a negative correlation with ideation effectiveness. Next, the second half of the mediation relationship was examined between sketch detail and ideation effectiveness. Word count and view count showed negative correlations with all ideation metrics across the pre and post-tests. Hypothesis 2b was partially confirmed. Both representation and texture/shading were independent of ideation effectiveness. However, word count and view count were negatively correlated with almost all ideation effectiveness measures both before and after sketching instruction. As designers elaborate through words and extra views it correlated with less productive idea generation. The effect size for this relationship was strongest with the variety measure showing that participants who elaborated more covered less of the solution space than participants who did not.

4.3.2 Structural Equation Model (SEM)

A structural model was created of the mediation relationship to analyze interactions and overall fit. Structural equation models (SEM) is a statistical method to evaluate the relationships between multiple observed or latent variables at the same time (Schumacker & Lomax, 2004). It is leveraged to test groups of hypothesized relationships and their interactions. In particular, SEM is useful for testing mediation relationships because all relationships with the mediating variable can be evaluated simultaneously. Not all variables were included in the SEM for these analyses. Precision, smoothness, and speed were excluded from the SEM analyses because the missing data for these variables would constrain the sample size for the broader analysis and because of their lack of relationships with sketch detail and idea generation in the correlations. The hypothesized model is shown in Figure 4.3.

The latent variable for sketching skills was calculated as a combination of the quality ratings from the three test sheets of the Sketching Foundations Test – the camera sketch, cylinder sketch, and cube sketch. Sketch detail was modeled as separate factors – Texture/shading, representation, and elaboration. While these factors are all part of the construct of "sketch detail", they are independent of each other and therefore represent independent constructs as shown in Table 4.2 and Table 4.3. Only word count and view count were modeled together through the latent variable elaboration because both measures were strongly correlated. Lastly, ideation effectiveness was measured as a combination of the three effectiveness measures – quantity, variety, and novelty. The three measures were strongly correlated with one another. The model was also evaluated for each measure individually and similar results were found to those of the composite ideation effectiveness measure described below. The relationships between the latent variables represent the hypothesized anticipated relationships shown in Figure 4.1. Sketching skill was hypothesized to have a direct impact on ideation effectiveness. The relationship between sketch skill and ideation effectiveness was also hypothesized to be mediated by sketch detail – this is represented as the arrows from sketch skill to texture/shading, representation, and elaboration, and the arrows from the sketch detail variables to ideation effectiveness. Lastly, DSEI was also hypothesized to have an impact on ideation effectiveness, and this is modeled as a direct relationship.

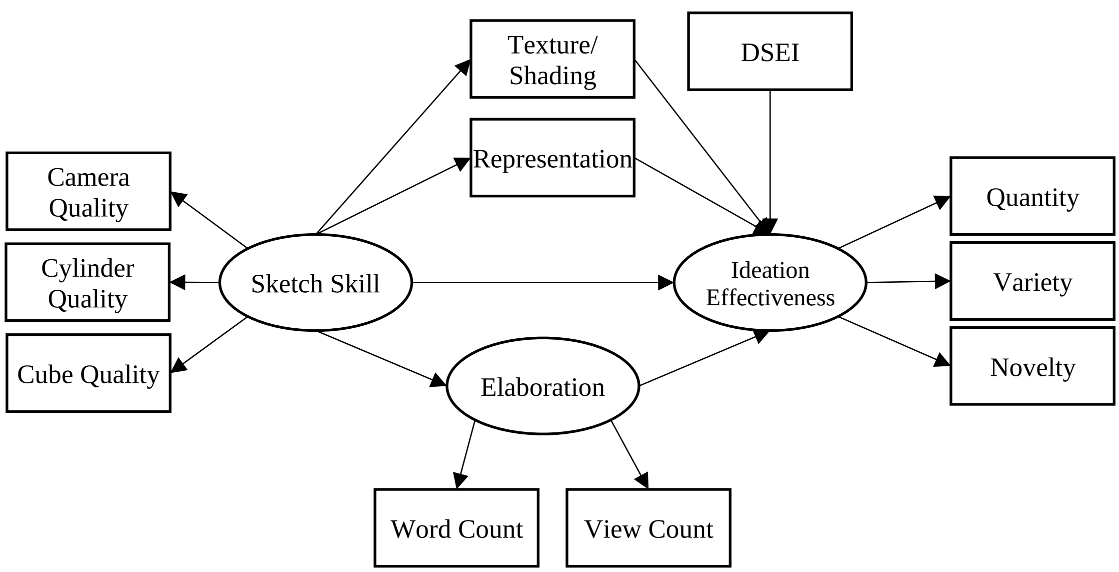


Figure 4.3: Structural equation model of the mediation effects of sketch detail on sketching skills and ideation effectiveness

Initial analysis showed that the relationships with both DSEI and texture/shading did not significantly contribute to the model, and, therefore, they were excluded. A modified model was analyzed with sketch skill, elaboration, representation, and ideation effectiveness. The models and standardized regression coefficients for this analysis are shown in Figure 4.4.

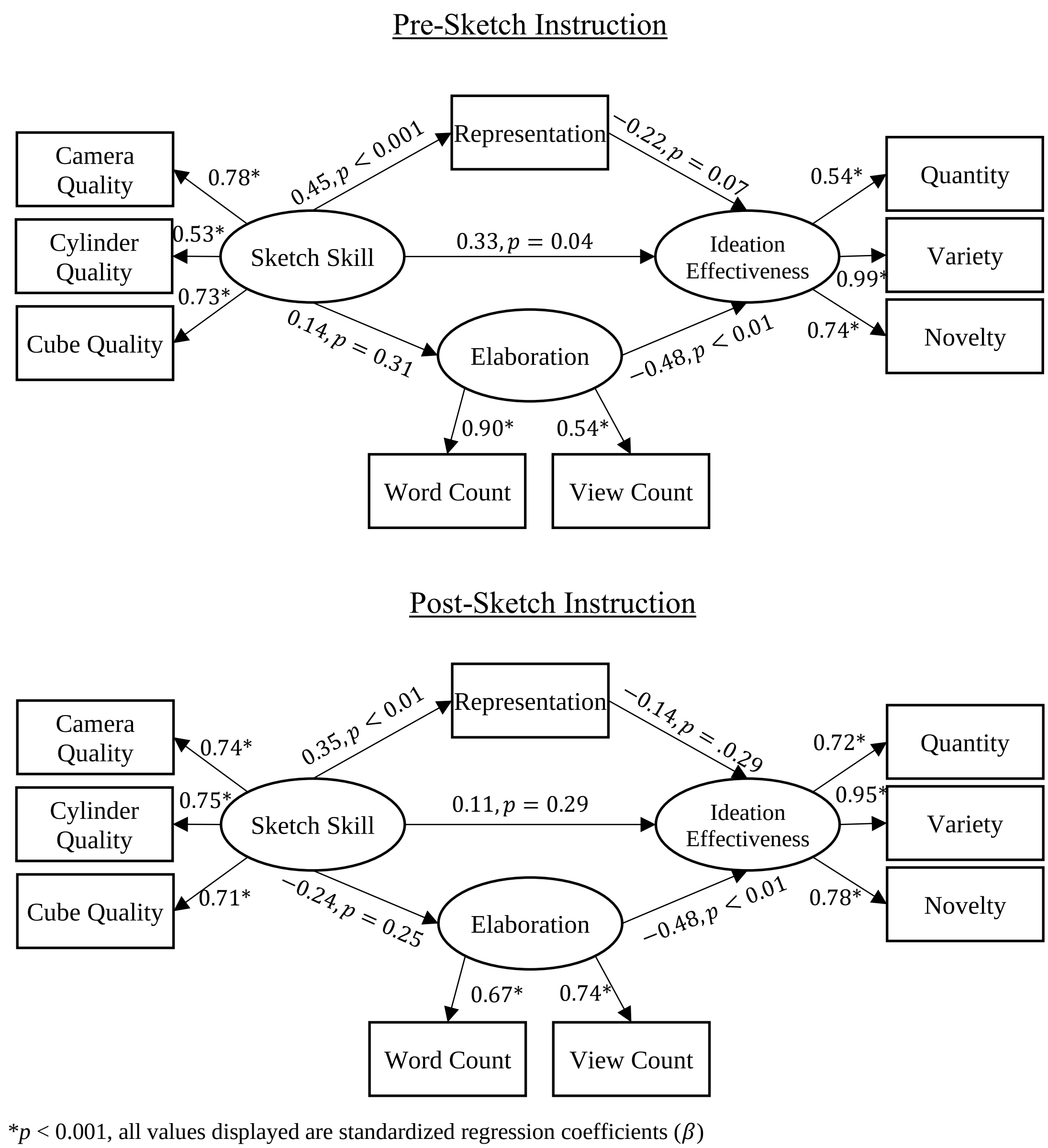


Figure 4.4: Modified SEM models and regression coefficients for pre and post-sketching instruction

Both models were fitted using SEM with the estimator as MLR (maximum likelihood with robust standard errors). The robust estimator was used to account for some of the variables not being normally distributed. All calculations were conducted in R using the lavaan package (Rosseel, 2012). The modified models in Figure 4.4 still contained relationships that were not significant between the latent variables. Further exploration was conducted through analysis to find the model that best fits the data. The final structural equation models are shown in Figure 4.5.

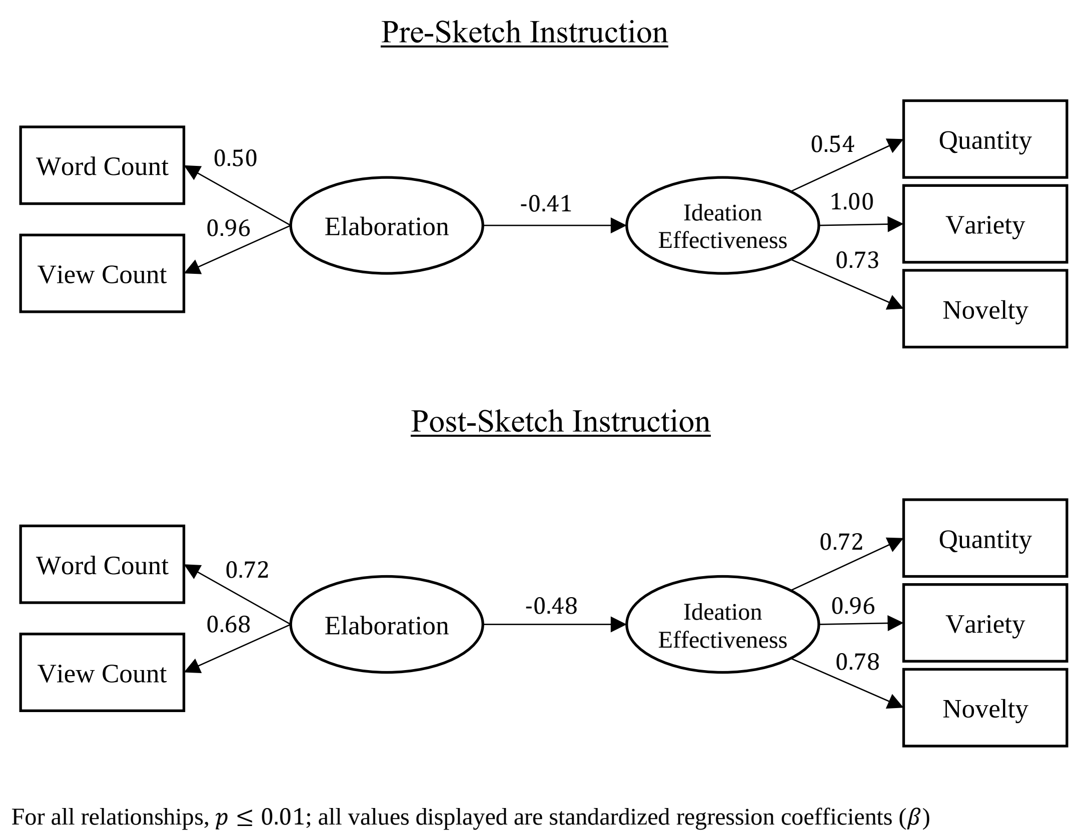


Figure 4.5: Final SEM models for pre- and post-sketching instruction

The models show that sketch detail is not a mediator for sketching skills and ideation effectiveness. While sketching skills significantly predict representation, representation did not significantly predict ideation effectiveness. Likewise, sketching skills do not significantly predict elaboration, but elaboration significantly predicts ideation effectiveness. The final models in Figure 4.5 show the removal of representation and sketching skills because they did not have any significant impact on ideation effectiveness. Even though mediation was not present, this does shed light on the relationship between sketching skills and ideation effectiveness. Sketching skills are independent of elaboration through views and words. This suggests another characteristic is driving elaboration. Understanding those factors could help improve students sketching behavior. Lastly, sketching skills did have a significant direct effect on ideation effectiveness in the pretest model.

The fit indices for the structural models that were analyzed are shown in Table 4.4. They show that the final model fits the data well.

Table 4.4: Fit indices for structural equation models

	Hypothesized Model (Figure 4.3)		Modified Model (Figure 4.4)		Final Model (Figure 4.5)	
	Pre	Post	Pre	Post	Pre	Post
χ^2	280.4	350.6	253.8	331.1	156.2	205.4
df	55	55	36	36	10	10
p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CFI	0.995	0.983	1.000	1.000	1.000	1.000
RMSEA	0.017	0.036	0.000	0.000	0.000	0.000
SRMR	0.084	0.068	0.037	0.045	0.036	0.012

4.3.3 Improvements Over Instruction

RQ3. To what extent does perspective sketching instruction improve sketching skills, drawing self-efficacy, sketch detail, and ideation effectiveness for entry-level engineering students?

To address the second research question, paired t-tests were conducted over the course of sketching instruction to understand how engineering students improved on these constructs. Because a large number of independent tests were conducted simultaneously, steps were taken to control for the experiment-wise Type I error rate. First, an omnibus repeated measures MANOVA was taken using all variables to check for any changes from the pre-instruction measures to the post. The MANOVA was significant ($F(12,41) = 13.28, p < 0.001$) showing at least one of the dependent variables significantly changed from pre to post. Second paired t-tests were for all variables from pre to post to determine which significantly changed. To account for Experiment-wise Type I error rate, a Holm-Bonferroni correction was applied (Abdi, 2010). The Holm-Bonferroni method adjusts the p-values to ensure that the experiment-wise Type I error rate remains below $\alpha = 0.05$. Statistics and effect sizes are shown in Table 4.5. Both sketch quality and DSEI improved significantly over the course of instruction with large effect sizes. This is consistent with improvements in sketching skills from other studies (Weaver, Ray, et al., 2022). Of the sketch detail measures, representation and texture/shading improved with a small effect size over the course of instruction. Word count decreased with a large effect size. And finally for ideation effectiveness, only variety significantly changed over the course of sketching instruction. Variety decreased with a small effect.

Table 4.5: T-tests of improvement over sketching instruction adjusted using the Holm-Bonferroni correction

Variable		Pre		Post				
	n	*M*	*SD*	*M*	*SD*	*t*	*p*	Cohen's *d*
Sketch quality	100	7.22	2.10	9.18	2.27	-10.3	<.001	-1.03
Precision	53	90.0	2.16	90.4	1.78	-1.28	0.413	-0.176
Smoothness	53	70.8	4.52	71.5	4.00	-1.64	0.533	-0.226
Speed	53	279	116	293	116	-1.29	0.608	-0.177
DSEI	100	5.07	1.96	6.19	1.64	-8.22	<.001	-0.822
Representation	100	1.81	.642	1.95	.644	-2.19	0.245	-0.219
Word count	100	63.3	34.9	35.4	29.0	10.1	<.001	1.013
View count	100	2.20	1.28	2.02	1.12	1.42	0.640	0.142
Texture/shading	100	1.46	.487	1.57	.535	-2.01	0.333	-0.201
Quantity	100	12.7	4.46	11.91	5.49	1.66	0.595	0.166
Variety	100	12.1	5.74	10.8	4.99	2.20	0.271	0.220
Novelty	100	1.87	1.77	1.81	1.87	.299	0.765	0.30

H2: Sketching instruction has a positive effect on sketching skills, drawing self-efficacy, sketch detail, and ideation effectiveness. Hypothesis 2 is partially confirmed. Sketch quality and drawing self-efficacy increased significantly over the course of instruction with a large effect size. This is consistent with previous work (Weaver, Ray, et al., 2022). Sketch detail also improved: representation and texture/shading increased with small effect size, and word count decreased with a large effect size. However, the changes for ideation effectiveness were not in line with the hypothesis. Quantity and novelty did not significantly change, and variety significantly decreased over the course of sketch instruction. It is not surprising that we saw no increase in ideation effectiveness after finding that sketching skills and ideation effectiveness are largely independent or only weakly related.

4.3.4 *Overall Discussion*

To summarize, sketch detail illuminated some interesting interactions between sketching skills and ideation effectiveness. Sketching skills were correlated with representation style, but representation was independent of ideation effectiveness. Sketching skills were independent of the elaboration measures (word count and view count), but word count and view count were negatively correlated with ideation. Over-elaboration lead to reduced ideation – either participants became attached to their ideas and this reduced their desire to generate further concepts, or elaborating on the concept used up their time or their cognitive resources leaving them less time/effort to generate new ideas. The independence of sketching skills and elaboration is encouraging. Designers who have stronger sketching skills are not inclined towards spending more time on a sketch or design. If a designer was inclined towards using high elaboration and had high sketching skills, they could be a dangerous design team member. The higher quality sketches would likely lead to ideas being perceived as higher quality (Kwon & Kudrowitz, 2018), and the elaborated, detailed idea could potentially lead to fixation. The relationship with word count and view count lead to a clear recommendation for design practice: When generating ideas, designers should make descriptions as concise as possible. This will not only lead to potentially better idea generation, but leaving some ambiguity in concept descriptions could lead to more creative misinterpretations that could spur on new ideas (Shah et al., 2001).

The overall benefits of sketching skills for idea generation are mild. Designers with stronger sketching skills were more inclined to represent ideas in 3 dimensions over 2. Further, representation increased over the course of sketching instruction showing that designers felt more comfortable at a higher level of representation after learning to sketch. This increased representation could prove beneficial to idea generation giving students a broader range of ways to sketch a concept. Sketching skills showed weak correlations with idea generation measures only after sketching instruction. This shows that students with higher skills and a little sketching instruction are slightly more inclined to generate more ideas. The effect size for this relationship is still small though showing that sketching skills do not have a large impact on engineering design ideation.

Sketch detail proved to be an illustrative measure demonstrating the nuanced relationship between sketching skills and idea generation. The measures were largely independent of one another and related to the constructs in the study differently. These separate mediating relationships helped flesh out important principles at play in this study. The authors recommend that future studies wishing to incorporate sketch "complexity" (McGown et al., 1998) or "level of detail" (Song & Agogino, 2004) consider using the separate measures of sketch detail.

4.4 Limitations

This study is not without its limitations. The length of time for idea generation may have had an adverse impact on some of the relationships between sketching skills and idea generation. Allowing 45 minutes for concept generation meant that students had the freedom to generate many ideas, but often students were not sketching the entire time during idea generation. This has the potential to add noise to the study by not pushing students to their sketching potential in a shorter time window. Previous research showed a connection with sketching skills and sketching over the course of several weeks (Yang &

Cham, 2007). Therefore, given a longer window for ideation, we hypothesized that sketching skills would still influence sketch frequency. Also, the purpose of this study was to look at their fully fleshed out ideation, so a longer time limit was preferable.

Second, the design problems limit the external validity of the study. The peanut sheller problem and corn husker problem are commonly used engineering design problems, but they are potentially not as demanding on spatial visual reasoning as other mechanical design problems may be. Previous research shows that designers use sketches to reason with a design space (Goldschmidt, 1991; Suwa et al., 1998). Sketches can illuminate visual complexity that is difficult to grasp in a designer's mind's eye. Design problems that leverage complex configurations or orientations may require more of a designer's sketching and spatial visualization abilities. Therefore, the relationships between sketching skills and ideation could be different under different circumstances. Future work should explore relationships under different design prompts. Lastly, with data collected in an entry-level course, most of the participants were inexperienced designers and future work should evaluate more experienced designers. This limits the external validity of the study.

4.5 Conclusion

Sketching has been emphasized in design research for some time and its benefits for designers are clear. However, there is still more to understand about the importance of sketching skills in design. This question is critical for engineering education and practicing designers alike to better understand how to prioritize sketching skill development. This study provided additional understanding along these lines examining how sketching skills impacted the critical task of concept generation in mechanical design. We found that sketching skills had a mild positive correlation with ideation effectiveness after sketching instruction. Sketch detail explained more of the variance in ideation effectiveness, however. Word count and view count were moderately negatively correlated with ideation effectiveness demonstrating that elaborating on design concepts had an adverse effect on overall ideation. Word count and view count were independent of sketching skills though. These results lead to clear recommendations for future design practice: Designers should be concise during idea generation minimizing text and elaboration of the sketch. Future work will examine how sketching skills impacts behavior during a design project.

CHAPTER 5. PREDICTORS OF SKETCHING BEHAVIOR

Designing without sketching is like trying to run with your arms tied behind your back – yes, you can do it, but it isn't going to help you get to the finish line. Freehand sketching is an integral part of the design process (Cross, 2001; Dym, Agogino, Eris, Frey, & Leifer, 2005; Ferguson, 1994). Sketching reduces the cognitive workload for the designer (Bilda & Gero, 2005), sketching is essential for communication (Goldschmidt, 2007), and sketching provides designers a fast visual representation to guide design decisions (Suwa & Tversky, 1997). Freehand sketching is a powerful tool during the conceptual design phase and beyond that needs to be leveraged more effectively (Ullman et al., 1990).

Sketching has been shown to positively correlate with design outcomes (Song & Agogino, 2004; Yang, 2009) demonstrating that more frequent sketching during design promotes good designs. The decisions we make earlier in the design process have the greatest impact on design outcomes (Dieter & Schmidt, 2009; Tan, Otto, & Wood, 2017). Sketching enables designers to reason with their designs and learn from them (Goldschmidt, 1991). A fast and fluid visual representation allows real time evaluation and improvement of design ideas, so it makes sense why the design process is benefitted by frequent sketching. Protocol studies have shown that designers don't just use sketches as external memory, but they leverage sketches as visual settings in which to solve design problems (Suwa et al., 1998). However, it seems, based on prior literature and this study that engineering students may not be receiving support for their sketching skills, and they are not using sketching effectively (Westmoreland et al., 2011).

Studies of engineering design projects looked at how students are using sketching in capstone design reports (Westmoreland et al., 2011). Students documented their entire process in their capstone design reports. In the conceptual design chapter of their reports, they were asked to provide at least 5 sketches of contemplated concepts for their project. The capstone course did not evaluate sketches for quality, but the authors hypothesized that the students would include the highest quality sketches for their reports. They found that graduating engineering students are largely sketching at low levels of detail and exhibiting low sketching skills. Engineering students often receive insufficient sketching education, and this lack of training results in engineers not using sketching effectively in the design process. Engineers' lack of understanding of the importance of sketching (Schmidt et al., 2012) and lack of sketching ability could therefore have negative impacts on their design outcomes or on the contribution of an individual designer (Kwon & Kudrowitz, 2019).

Therefore, understanding catalysts and inhibitions around engineering designer sketching behavior is of critical importance. Unlocking this tool could have positive design outcomes for future projects. Researchers have tested some interventions to encourage sketching behavior with positive results. Students used sketching more effectively after being taught a brief lesson on the value of sketching (Ruocco et al., 2009), when they were explicitly assigned to sketch (Schmidt et al., 2012), and when given a two lecture workshop on freehand sketching technique (Booth, Taborda, Ramani, & Reid, 2016). These studies hold promise that designers' sketching behavior is easily influenceable. However, there is still more to be understood about what encourages designers to sketch during design.

The goal of the current chapter is to further understand some of the implicit factors that make designers more or less inclined to implement sketching behavior in design.

Understanding underlying factors associated with sketching behavior will provide insight into designers' motivations for using specific design tools. This insight could then potentially be leveraged to further improve designers' use of sketching. In this chapter, we explore several factors potentially connected to a designers' sketching behavior. Sketching behavior is measured through self-report data on how frequently students used sketching during the design process and what tasks they used sketches to accomplish.

5.1 Research Questions and Hypotheses

The overarching research question for this project is the following:

RQ: What factors influence sketching behavior in a design project course?

This research question is executed by evaluating engineering students on a variety of measures likely connected to sketching behavior such as sketching skills, spatial visualization, and self-efficacy. Then students sketching behavior is surveyed in two design courses to understand how these factors influence their use of sketching. Students were evaluated in three different courses: (1) an entry-level design and graphics course, (2) a sophomore-level design project course, and (3) a senior-level capstone design course. In the entry-level course, students were evaluated on sketching skills and spatial visualization skills. In the entry-level course, students received one of two types of sketching instruction: traditional engineering sketching instruction or perspective sketching techniques derived from industrial design. In the sophomore and capstone design courses, students were surveyed after completing their projects on their engineering design self-efficacy (Carberry et al., 2010), demographics, and how frequently they used sketching during the design process. Analyses between these factors will reveal relationships with sketching behavior.

We are interested in reported sketching behavior and any differences in behavior between the two design courses. Primarily, we are interested in how the measured constructs predict sketching behavior. The specific research questions addressed in this chapter are the following:

RQ 1. To what extent does sketching behavior differ between a sophomore-level and capstone design course?

RQ 2. To what extent do the following constructs predict sketching behavior during a design project course?

2.1. Sketching Skills

2.2. Spatial Visualization Skills

2.3. Type of Sketching Instruction

2.4. Engineering Design Self-Efficacy

2.5. Gender

Each of the constructs measured is hypothesized to predict sketching behavior in engineering designers. Provided below is the current supporting evidence for examining each of the factors included in the study.

If engineers are more versed in sketching, then the cognitive workload associated with producing a sketch will be reduced and the skill may be more readily accessible as they are designing. Essentially, improving skill could reduce inhibition towards using sketching as a tool (Booth et al., 2016). Through a study of engineering logbooks, researchers found that there was a positive correlation between sketching ability and frequency of sketching (Yang & Cham, 2007). The current study looks at sketching skills measured in an entry-level engineering graphics course and sketching frequency in future design courses. This relationship speaks to the power and the longevity of the relationship between sketching skills and sketching frequency. We hypothesize that differences in sketching ability will be maintained throughout the engineering degree. Sketching is not taught outside of the entry-level course, but students do have opportunities to leverage sketching on design projects throughout the curriculum. Therefore, we predict students' sketching skills will influence their use of sketching on future projects.

H2.1: Engineering students' sketching skills have a positive effect on frequency of sketching during a design project.

Spatial visualization skills in this study are evaluated using the PSVT:R (Yoon, 2011) and the MRT (Peters et al., 1995). Both tests evaluate ability to mentally rotate images. Yang and Cham (2007) found a negative correlation between a mechanical recall task and students frequent use of sketching in design notebooks. They posited that this negative relationship could potentially be due to improved spatial skills exhibited in the mechanical recall task. If a designer can see more in their minds eye, then potentially they would not need to sketch as often. It has been shown that expert architects design quality is not significantly impacted by removing the use of sketching for short design tasks (Bilda, Gero, & Purcell, 2006). The current study employs commonly utilized tests of spatial skills to further shed light on the relationship between spatial visualization and sketching.

H2.3: Engineering students' spatial visualization skills have a negative correlation with frequency of sketching during a design project.

Freehand sketching skills are only taught minimally in some engineering curriculums (Weaver, Ray, et al., 2022). Some engineering programs have begun to incorporate new sketching techniques, such as perspective sketching, that emphasize freehand sketching abilities more than the traditional engineering sketching curriculum did (Weaver, Ray, et al., 2022). These sketching techniques hold the promise of improving student sketching behavior during design by giving students stronger freehand sketching skills. The current study compares students who received two-point perspective sketching instruction and students who received traditional sketching instruction. Traditional engineering sketching instruction is focused on transformations between isometric and orthographic views and largely focuses more on visual understanding and precision than artistic visualization. Students are only asked to sketch representations in one specific angle (isometric) and there is no teaching on line quality or other visualization practices. . Perspective sketching focuses more on developing freehand sketching abilities by having students represent objects from a variety of views and providing a framework to depict complex shapes. Perspective sketching instruction, rooted in industrial design, provides a stronger artistic background that teaches more elements of style such as line quality, lighting, and shading (E. Hilton et al., 2016; Hilton, Linsey, et al., 2018). We predict that the emphasis on freehand sketching abilities in the perspective instruction will increase frequency of sketching in later design courses.

H2.2: Students who received two-point perspective sketching instruction sketch more frequently than students who received traditional engineering sketching instruction.

Designers' self-efficacy plays an important role in their behavior. Carberry et al. (2010) conducted validation of a survey to evaluate Engineering Design Self-Efficacy.

They showed that the survey instrument differentiated effectively between designer experience levels. EDSE has also been shown to correlate with other design related activities such as involvement in makerspaces (Hilton, Talley, Smith, Nagel, & Linsey, 2020). How confident students are in the arena of design could predict how readily they will put pencil to paper during a design project.

H2.4: Engineering students' engineering design self-efficacy has a positive effect on frequency of sketching during a design project.

There is some conflicting evidence on how sketching behaviors differ between genders among designers. A study of industrial design students showed that men were stronger sketchers and were more confident in their sketching abilities than women (Barnhart & Walters, 2018). However, a study of engineering design logbooks found that women sketched as frequently as men did during the design process (Song & Agogino, 2004). Lastly, a study of idea generation found women generated more sketches than men, but there was no difference between sketch quality or style between genders (Das, Huang, & Yang, 2022). These conflicting results suggest a lack of understanding of gender differences in sketching behavior and suggest the need for further data. Because of the conflicting reports, we predict no difference between the two groups.

H2.5: Male and female engineering students will not sketch at a significantly different frequency in design courses.

These measures will shed light on why designers sketch during the design process. Understanding motivations and other underlying factors will improve our understanding of design behavior and will inform interventions to help designers sketch more frequently during the design process.

5.2 Methods

5.2.1 Research Design

The goal of this study is to examine engineering students sketching skill development in their early course work and track how that impacted behavior in future design project courses. Students were studied during the only early course where they were taught sketching skills, and then surveyed in two later design project courses about their use of sketching during the design projects. Data for this study were collected from three courses: an entry-level design and graphics course, a sophomore-level design project course, and a senior-level capstone design course. The aim of the research was to follow students as they progressed through the engineering curriculum. Therefore, data collection was conducted in each course for a number of semesters to maximize the number of students that would participate in all data collection points. Data were collected in the entry-level course in the Fall 2015 and Spring 2016 semesters. Data collection in the two design project courses was conducted alongside a separate project studying students use of makerspaces on academic campuses (Hilton et al., 2020). Data were collected in the sophomore-level design course in the Spring 2018 and Fall 2018 semesters. The semesters of data collection for the sophomore-level design course did not correspond with the timing of the data collection in the entry-level course due to the difference in timing of the two separate research project. Data were collected in the capstone design course in all of the semesters between the Fall 2017 and Fall 2019 semesters.

In the entry-level graphics course, students are taught sketching for the first third of the class (5 weeks) and then CAD for the second two thirds. During the course, students were tested on sketching skills and spatial skills. Students were evaluated on these measures before and after receiving sketching instruction to track their development. Pre-sketching instruction evaluations took place in the first week of classes, and post-sketching instruction evaluations took place in the fifth week of classes immediately after the sketching instruction concluded. Students were assigned to one of two conditions of sketching instruction: traditional engineering sketching instruction or perspective sketching instruction, which has a larger emphasis on freehand sketching abilities. Students were assigned to the sketching instruction based on which section of the course they signed up for and which professor was instructing that section. The researchers could not impose a random course assignment on students to respect students' autonomy in choosing their own course schedule.

Data were collected in the sophomore-level and capstone design course through surveys on students' use of sketching during the course, demographic factors, and their Engineering Design Self-Efficacy (EDSE). The data collected in each course is displayed in Figure 5.1. These data sources allow us to study how sketching skills, spatial skills, sketching instruction, and self-efficacy impact the use of sketching during the design process. Outlined below are the details of the participant characteristics, the sampling procedures, and the independent and dependent measures used in the study.

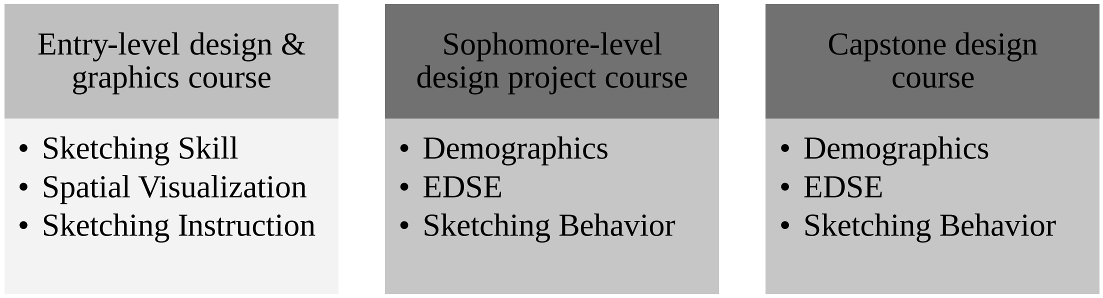


Figure 5.1: Breakdown of data collected in each course in the study

5.2.2 Participants

The primary focus of this study is students' sketching behavior in the two engineering design project courses during their sophomore and senior year. Because sketching behavior is the construct of interest, data used from the entry-level graphics course was limited to only those students who later participated during one of the two design courses. In all, 769 students participated in the design course surveys. There was limited overlap in students who participated in both design courses: 374 students participated in the sophomore-level design course and 431 students participated in the capstone design course data collection. Of the 769 students, 185 were women, 531 were men, 1 was non-binary, and 52 preferred not to disclose. The group was racially/ethnically diverse: 463 White, 166 Asian, 40 Black, 12 Hispanic, 5 Middle Eastern, 35 identified as two or more races, and 48 students preferred not to disclose. About 15% of participants (118 of the 769) identified as first-generation college students. The vast majority of students were pursuing degrees in mechanical engineering.

There were only a small number of students participated in both the entry-level graphics course study and the sophomore-level design course survey ($n = 12$). This small sample size was due to a misalignment of the data collected in the entry-level course and the sophomore-level design course. Because of the small sample size analyses were not conducted between the entry-level course measures and the sophomore-level course data. However, there were 157 students who participated in the entry-level course and the capstone design survey. This allows analysis on how sketching instruction and sketching skills impact future design performance. The number of semesters between the two courses varied for participants. Table 5.1 shows the distribution of how many semesters there were between the two courses for students who participated. The mean and median number of semesters between the two courses was 6, and the mode was 7 semesters.

Table 5.1: Number of semesters (amount of time, not accounting for enrollment) between completing the entry-level design & graphics course and the capstone design course

Number of Semesters	Count
3	2
4	19
5	17
6	46
7	58
8	15

5.2.3 Sampling Procedures

Data in the entry-level engineering design and graphics course were collected from 9 sections of the course in the Fall 2015 semester and another 9 sections of the course in the Spring 2016 semester. All research activities were conducted during class time. Students were asked to complete a task of sketching skills followed by a survey. All participation was voluntary. Students were offered the choice of extra credit in the course or a small monetary compensation for participating.

Participants in the two design courses were recruited from all sections of the courses during the semesters of data collection. At the end of the semester, students were offered the opportunity to complete the survey. Participation was entirely voluntary. Students were offered the choice of extra credit in the course or a small monetary compensation for participating. Data collection in all courses was approved by the institutional review board.

5.2.4 Design Project Courses

Capstone design at Georgia Tech is a one semester design project course. Students form teams and work on all aspects of a project from problem definition to functioning prototype. Student teams work with sponsors or on individual projects. Each team has a faculty advisor that they have regular meetings with to guide their project. The course ends with a large expo to show off the student projects where awards are given for the best designs.

The sophomore-level design course in which data were collected differs in several way from capstone. Overall, the course is more scripted than a capstone design project.

Design teams are given specific deliverables that are benchmarked in design reports. Each consecutive report asks them to implement and document a series of design tools. In the design reports, students are tasked with explicitly creating sketches for idea generation. This is significantly different than capstone, where sketching may only be mandated by some faculty advisors. Another large difference is that the sophomore-level design course incorporates three different design projects to help expose students to more of the design process. The first two projects are short – one is only a couple of days, and the second one only a few weeks. The last project takes up the majority of the semester and is the focal point for the course, but it is not the entire semester like capstone. The course ends with a large design competition focused on the prototypes constructed for the last and largest project.

5.2.5 Sketching Instruction

Students in the entry-level graphics course received one of two types of instruction: traditional engineering sketching instruction or perspective sketching instruction. Traditional engineering sketching instruction consisted of sketching isometric and orthographic views focused on developing spatial visualization skills. Perspective sketching instruction has a larger emphasis on freehand sketching providing a framework for developing complex 3D forms. A detailed description of both types of sketching instruction is provided in CHAPTER 3.

5.2.6 Measures

In the entry-level engineering design and graphics course, students were evaluated on sketching skills using the Sketching Foundations Test (E. C. Hilton et al., 2016), and students were evaluated on spatial skills using the PSVT:R (Yoon, 2011) and the MRT (Peters et al., 1995). In the two design courses, students' self-efficacy was evaluated using the Engineering Design Self-Efficacy instrument (Jaison et al., 2021), and students' sketching behaviors were assessed through survey questions at the end of the semester. In all three courses, students were also surveyed about their involvement in makerspaces and other extracurricular activities, but that data is not evaluated in the current study. Results on the makerspace involvement survey questions can be found in (Hilton et al., 2020).

5.2.6.1 Sketching Foundations Test

The Sketching Foundations Test (shown in Appendix A) is a test of basic sketching skills developed by E. C. Hilton et al. (2016). The test is focused on the basic elements of 2-point perspective sketching although no real content knowledge of 2-point perspective is required. Sketching all components of the test assuming isometric views would achieve the same skill scores. The test begins with lines and progresses to a combination of primitives with a sketch of a simple camera. The final sheet of the test (the camera prompt) is shown for example in Figure 5.2. The sketch is completed on paper with either a pen or pencil and the use of straight edges were prohibited. Students were not given a time limit for completing the test.

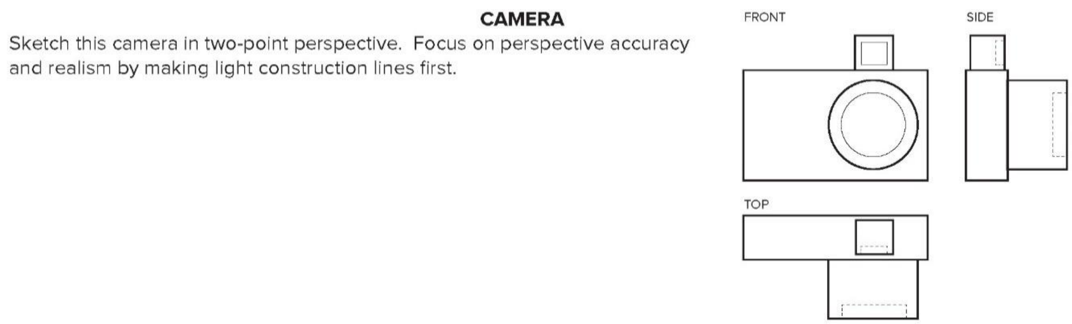


Figure 5.2: Sketching Foundations Test – camera prompt

Each sheet of the test was evaluated by two independent raters for each student that is included in this study. Raters were told to assess each sketch based on the overall quality of the sketches. The rating process leaned on the raters' previous experience with sketching to inform their understanding of sketch quality. One rater was a graduate student in industrial design with extensive sketching skills and a strong knowledge of the perspective sketching technique. The second rater was a graduate student in mechanical engineering with training in perspective sketching techniques with considerable experience evaluating sketches. Inter-rater reliability (IRR) between the raters was evaluated using Krippendorff's alpha (Krippendorff, 2011). The average IRR for all ratings on all sheets was $\alpha = 0.69$, which shows substantial agreement.

Sketches were excluded from evaluation if they were incomplete, if the participant did not properly follow instructions, or if a straightedge was used as an aid. Participants sketch skill data were excluded if they were missing any component of the Sketching Foundations Test. Each sheet was evaluated on a scale from 1 to 5 with 5 being the highest sketch quality. Both raters evaluated all of the data in the study and an average of their ratings was taken. The final sketch quality score for participants was taken as the sum of the scores for each sheet. Therefore, the theoretical range for scores is from 8 to 40. The practical range of scores for this study was from 11.5 to 39.

5.2.6.2 Spatial Visualization

Spatial visualization skills were measured using two tasks of mental rotations challenges: the Revised Purdue Spatial Visualization Test (PSVT:R) (Bodner & Guay, 1997; Yoon, 2011) and the Mental Rotations Test (MRT) (Peters et al., 1995; Vandenberg & Kuse, 1978). The PSVT:R consists of 30 questions and was not timed for this study. The MRT is split into two sections of 12 questions each, each with a six-minute time limit. Both spatial visualization tasks were administered through an online survey.

5.2.6.3 Engineering Design Self-Efficacy (EDSE)

The Engineering Design Self-Efficacy (EDSE) instrument was developed by Carberry et al. (2010). The instrument consists of 36 questions broken down into four subsections. Participants are asked about their level of confidence, motivation, expectation of success, and anxiety with regards to 9 different activities associated with engineering design. Answer choices range from 0 to 100 incremented by units of 10. The four different elements are kept separate for analysis. Responses to the 9 items for each aspect of self-efficacy are averaged for analysis. The validity of the EDSE instrument has been examined through several lenses. The items showed strong inter-item reliability within each of the four factors of the self-efficacy instrument. The scale effectively differentiated between groups with differing levels of engineering expertise, and the four factors showed strong correlations between themselves with anxiety correlating negatively with the other factors (Carberry et al., 2010).

The EDSE data were checked for careless responses. Consistency indices can be an effective way to identify careless responses in data (Meade & Craig, 2012), another term for this is straight-lining (Vriesema & Gehlbach, 2021). This refers to when participants simply reply with the same value for a large number of questions. The consistency index used in this data was a maximum count of equivalent responses. Upon examining the distribution of maximum equivalent responses, it was clear that it was a multimodal distribution. There was a clear mode at 36 meaning that a group of participants had selected the same answer choice for the entire instrument which shows a clear level of carelessness. There was also a mode at 26/27 meaning that a group of participants had selected the same value for 75% of the survey. Upon examining those responses, most of the students had responded with a value of 100 for all items in the confidence, motivation, and expectation of success aspects of the self-efficacy instrument. This showed a level of carelessness in this group of responses, and the mode demonstrated a significant break among those participants from the typical distribution of responses. Therefore, all participants who responded with a single value for more than 25 items on the survey were excluded from the EDSE data. This removed 109 out of the 805 EDSE responses, which is 13.5% of the sample. This level of careless responses is consistent with levels found in other undergraduate populations (Meade & Craig, 2012).

5.2.6.4 Sketching Behavior

Sketching behavior was evaluated through three survey items asking about sketching behavior during the design project course shown below in Table 5.2.

Table 5.2: Survey items evaluating sketching behavior

Q#	Subject	Questions	Answer Choices
Q1	**General Sketching Frequency**	How frequently did you create sketches by hand for your [Capstone] classwork this semester?	a. Never b. 1-5 times throughout the semester c. 6-15 times throughout the semester d. 1-2 times per week e. 2+ times per week
Q2	**Sketching for Prototyping**	In regards to building prototypes for your [Capstone] Project, how often do you draw a sketch by hand before making a new prototype?	a. I did not build a prototype for any class projects this semester b. I have never created a hand-drawn sketch of my prototype c. Only for the initial brain-storming process (before building a physical prototype) d. Only when creating a completely new prototype e. Before major adjustments or redesigns f. Before every adjustment or redesign
Q3	**Purposes for Sketching**	For what purposes did you create sketches by hand during for your Capstone Project this semester? (Select all that apply)	a. I did not create any sketches b. Free-body diagrams c. Idea Generation d. Communication with teammates e. Communication with TAs/Instructors f. Diagrams to assist with building prototypes

Q1 is a basic question of how frequently sketching was used throughout design. Q2 specifically targets sketching for prototyping because of the findings from Yang (2009). They found that dimensioned sketching early on in the design process correlated with positive design outcomes, and they hypothesized that dimensioned sketching is likely be connected to sketching for early prototyping. Therefore, sketching for prototyping was of particular interest because it could lead to understanding of success in design projects. Q2 was added into the surveys for the design courses after data collection had begun. Therefore, the sample size for this question is somewhat smaller. Q3 surveys sketching for specific purposes in design. In understanding designers sketching behavior, it is important to understand more than just the frequency of sketching, but also what specific sketching behaviors individuals have the most motivation/inhibition towards. Q3 was examined in two ways for the analysis. First, a count was taken of how many purposes for sketching respondents selected. This number ranged from 0 to 5 and speaks to the diversity of designers' use of sketching. Second, I examined each of the purposes for sketching separately to understand patterns relating to specific sketching behaviors.

5.3 Results

RQ 1. To what extent does sketching behavior differ between a sophomore-level and capstone design course? The analysis for this study examines self-reported sketching behavior in two distinct engineering design project courses. I first compared the sketching behavior and EDSE between the two course before examining predictors to better understand differences between the two courses. I first examined the responses to the sketching questions to understand the reported sketching behavior and any differences between the two design courses. The distributions of responses to the three sketching behavior questions are shown in Figure 5.3, Figure 5.4, and Figure 5.5.

The responses to Q1 (general sketching frequency) are shown in Figure 5.3. Very few students did not sketch at all during the semester. However, the mode for this question was the lowest response, "1-5 times throughout the semester," and this was the same in both design courses. This suggests that a large portion of students are not using sketching regularly during design. A Mann Whitney U-test showed that there was a significant difference in sketching frequency between the two courses ($U = 30{,}385, z =$

$-3.85, p < 0.001$) with a small effect size of $r = 0.16$ (Field, 2013). The sophomore design course reported sketching more frequently than the capstone design course. This could likely be because sketching is mandated for some of the design reports in the sophomore-level design course.

The responses to Q2 (sketching for prototyping) are shown in Figure 5.4. There were no significant differences between courses for the questions about sketching for prototyping ($U = 70{,}364, z = -0.93, p = 0.35$). This relationship also showed a very small effect size with $r = 0.03$. Looking at the responses to the sketching for prototyping questions, we see that the sophomore design course and senior design course had very similar distributions. This suggests that students sketching behavior for prototyping may be very consistent regardless of what type of project they are working on. Both design courses involve prototyping final designs. For the capstone course, prototypes are demonstrated at the expo, and for the sophomore level design course, prototypes are tested in a competition.

The responses to Q3 (purposes for sketching) are shown in Figure 5.5. There was not a significant difference for the number of purposes listed between the sophomore and capstone design course ($U = 36{,}182, z = -0.78, p = 0.43$). The effect size for Q3 was also small ($r = 0.03$). The mode for count of purposes of sketching was 3 for the sophomore design course and 4 for capstone design. Students were reporting using freehand sketching for a variety of purposes.

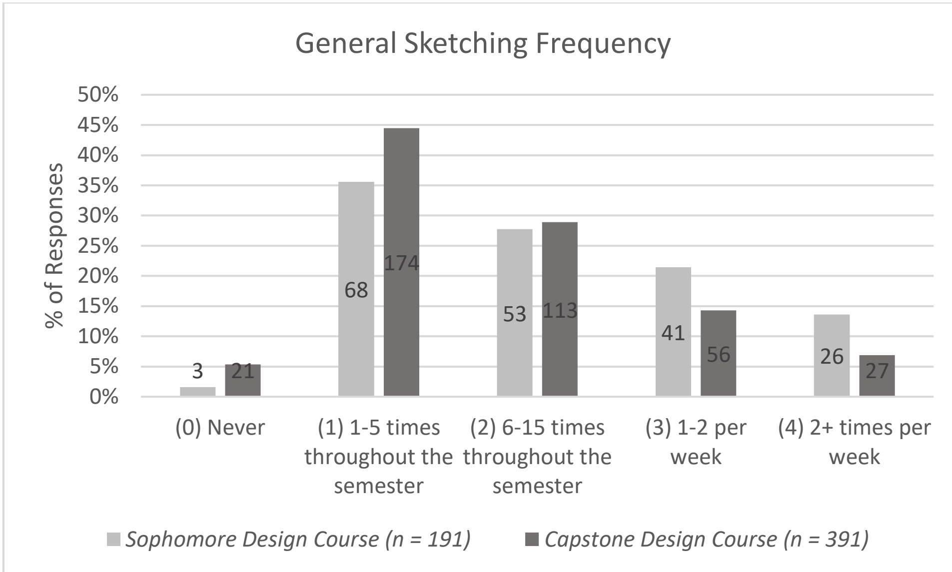


Figure 5.3: Distribution of responses to sketching behavior Q1 general sketching frequency

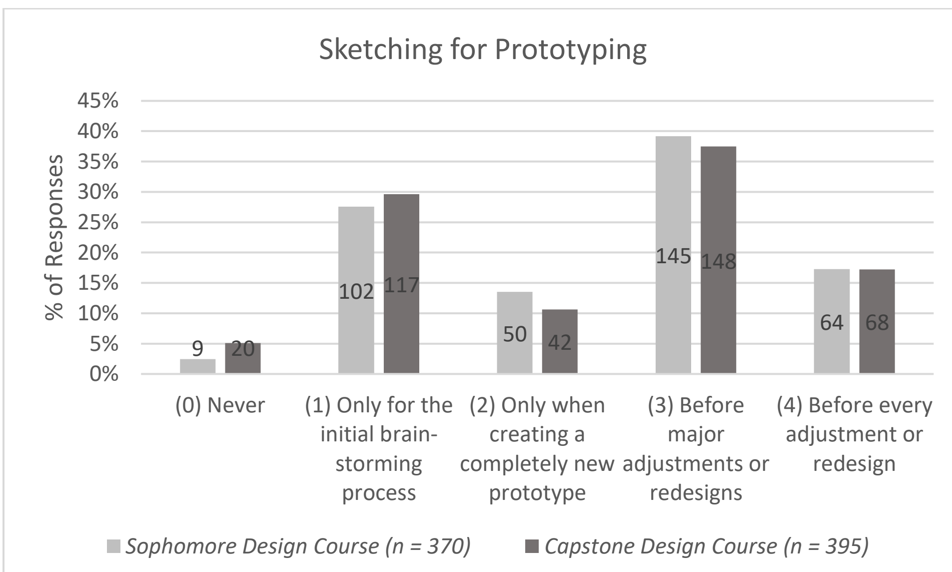


Figure 5.4: Distribution of responses to sketching behavior Q2 sketching for prototyping

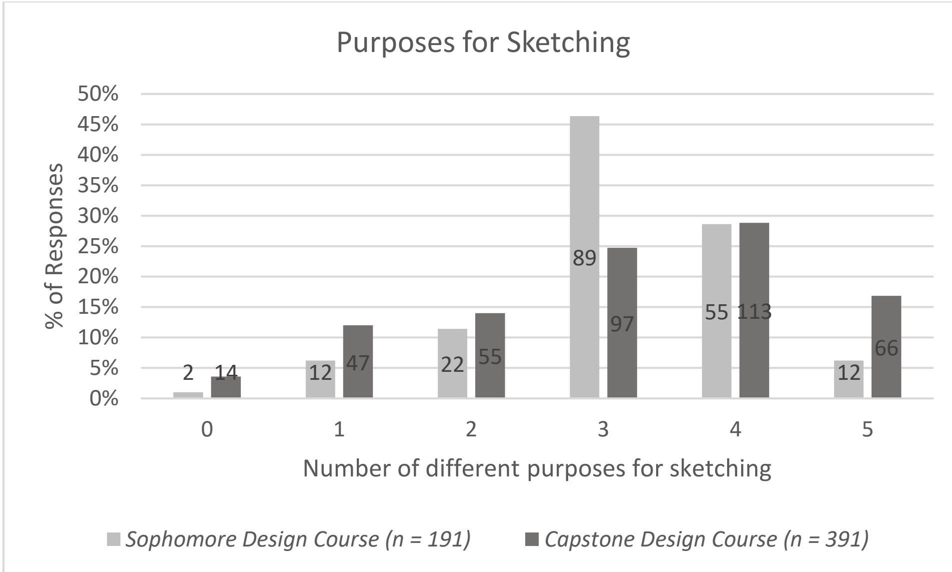


Figure 5.5: Distribution of responses to sketching behavior Q3 purposes for sketching

We then looked more closely at Q3 the specific purposes students reported creating sketches for, shown in Figure 5.6. In both courses, a majority of students reported sketching for idea generation, communication with teammates, and diagrams to assist with building prototypes. This reinforces the idea that most students use sketching for a variety of purposes in the design process, and this is consistent across these two design project courses. The shape of the distribution is similar across the two courses, but chi-square tests showed that there were differences in sketching frequency for some of the purposes for sketching. Students in the sophomore design course were significantly more likely to sketch for communication with teammates ($\chi^2(1, N = 584) = 20.11, p < 0.001, w = 0.19$) and to assist with building prototypes ($\chi^2(1, N = 584) = 26.43, p < 0.001, w = 0.21$). Capstone students were significantly more likely to sketch free body diagrams ($\chi^2(1, N = 584) = 40.30, p < 0.001, w = 0.26$) and for communication with

TAs/Instructors ($\chi^2(1, N = 584) = 7.83, p = 0.005, w = 0.12$). Both groups used sketching for idea generation at a similar rate ($\chi^2(1, N = 584) = 0.82, p = 0.36, w = 0.04$). The effect size index *w* suggests small effect sizes for most relationship ($w < 0.3$) (Colman, 2015). The strongest effect size was the difference in sketch frequency of free body diagrams.

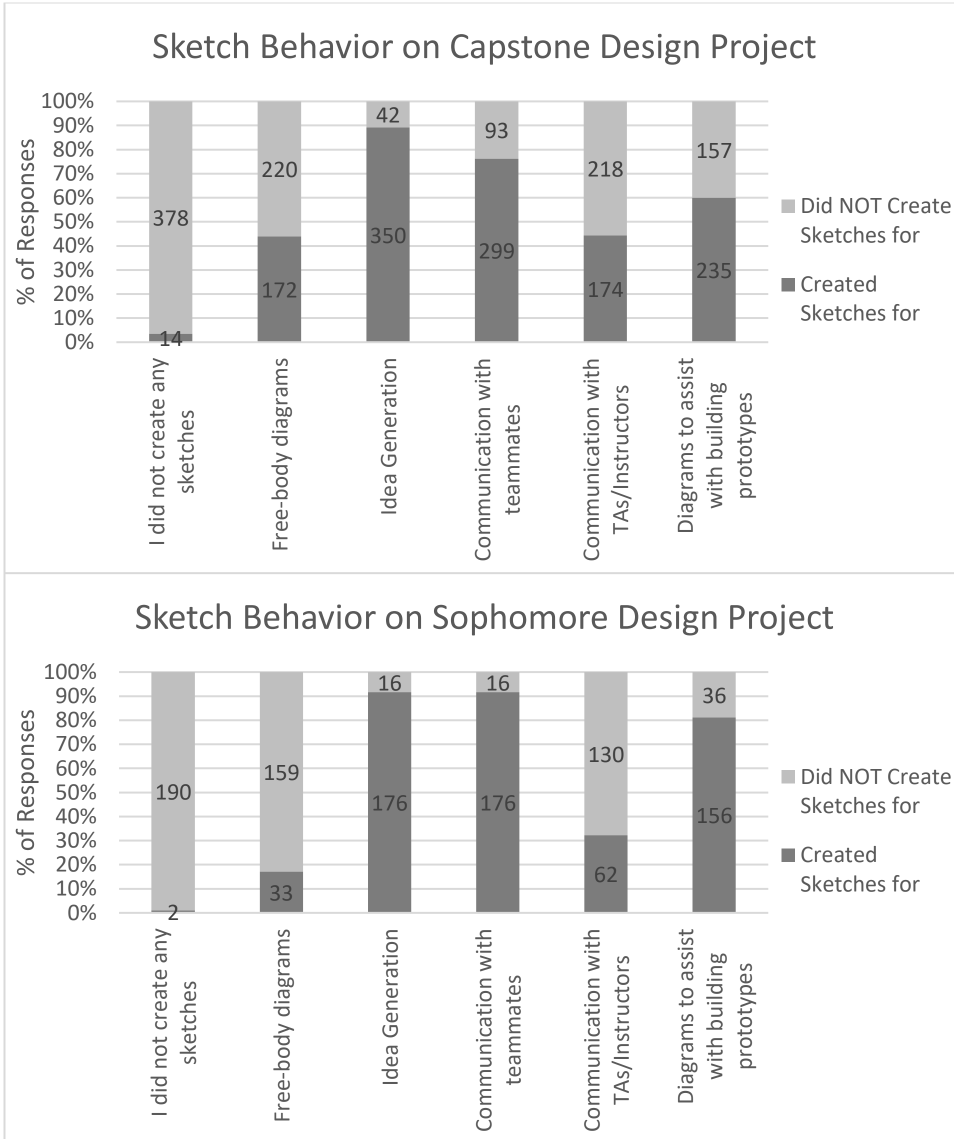


Figure 5.6: Distribution of Q3 purposes for sketching in sophomore design course (top) and capstone design course (bottom)

Lastly, the EDSE was compared between the two design courses to better understand differences in their design self-efficacy as this could change behavior. The EDSE averages for both courses are shown in Figure 5.7. There were no significant differences in EDSE for confidence $(t(694) = 0.676, p = 0.499)$, expectation of success ($t(694) = -1.126, p = 0.261$), or anxiety ($t(694) = -0.953, p = 0.341$) between the two courses. However, students in the sophomore design course reported higher levels of motivation ($M = 80.2, SD = 14.4$) than students in the capstone course ($M = 77.3, SD = 16.7$), $t(693) = 2.402$ ($p = 0.02$). This is not unexpected given that senior design students are likely to experience burnout at a higher rate leading to lower motivation. Higher motivation in sophomore design students could also explain why they reported sketching more frequently during the design process.

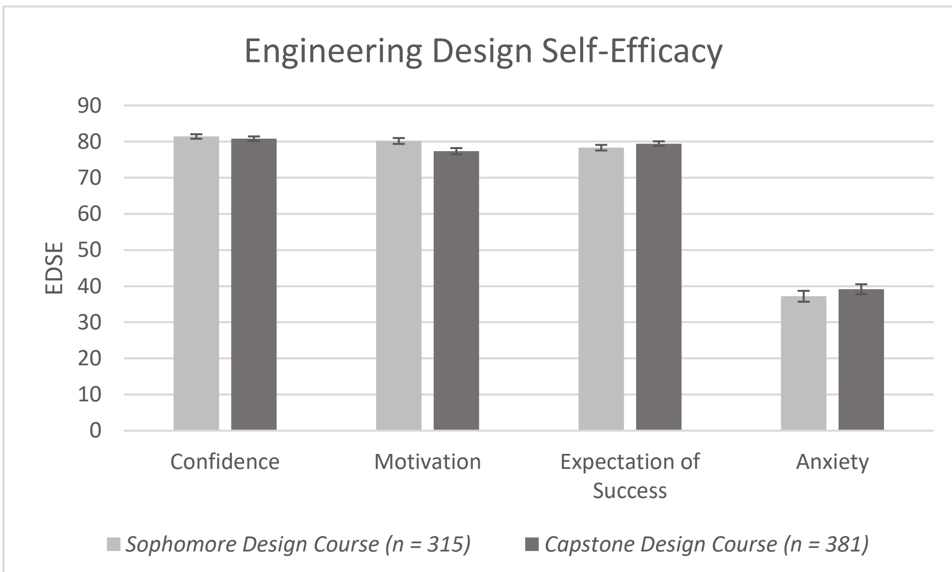


Figure 5.7: EDSE for sophomore and capstone design courses

RQ 2. To what extent do the following constructs predict sketching behavior during a design project course? To examine the extent to which the independent variables (sketching skills, spatial skills, type of sketching instruction, engineering design self-efficacy, and gender) predict sketching behavior, we explore correlations and regressions between them. For these analyses, it is helpful to note that there are essentially three data sets involved in this study. The first dataset is longitudinal data between the entry-level course and the capstone course. This dataset represents students who participated in the sketching and spatial visualization exercises their freshman year and then were surveyed again when they completed capstone six semesters later (on average). This data set allows us to analyze the extent to which sketching skills, spatial visualization, and sketching instruction predict sketching behavior in a future design course. The remaining two data sets are comprised of the survey data in the sophomore-level and capstone design course. In these surveys, students were asked about engineering design self-efficacy, demographics, and sketching behavior. These two data sets allow us to analyze the relationship between design self-efficacy, gender, and sketching behavior in both a sophomore-level and capstone design course.

RQ 2.1-2.2: To what extent do Sketching Skills and Spatial Visualization Skills predict sketching behavior during a design project course? To address the first two research questions, data is analyzed from the entry-level design and graphics course. These analyses examine how first-year sketching skills, spatial visualization, and sketching instruction predict sketching behaviors in a capstone design course, on average six semesters after the entry-level course. The responses to the sketching behavior questions constitute ordinal level data. Therefore, Spearman’s rho was used to analyze relationships of sketching skills and spatial skills with sketching behavior. Students completed evaluations of sketching skills and spatial skills before and after receiving sketching instruction. Both evaluations were examined to understand relationships before and after students received sketching instruction; they are denoted as “Pre” and “Post” in the tables below. The results are displayed in Table 5.3.

There was a significant correlation between both pre- and post-PSVT scores and general sketching frequency (Q1). The stronger predictor was the pre-PSVT measure with $r^2 = 0.068$. This shows a relationship, although weak, between students' entry-level spatial visualization skills and how frequently they sketch in a capstone design course. There was also a significant relationship between pre-sketch quality and Q3, the number of purposes for sketching ($r^2 = 0.037$).

Table 5.3: Spearman's rho correlations of sketching behavior questions vs. sketching skills and spatial skills

	General Sketching Frequency			Sketching for Prototyping			Purposes for Sketching		
	r	*n*	*p*	*r*	*n*	*p*	*r*	*n*	*p*
Pre-Sketch Skill	0.081	108	0.40	0.109	132	0.21	0.193*	109	0.04
Post-Sketch Skill	0.069	110	0.48	0.058	134	0.51	0.065	111	0.50
Pre-PSVT	0.260**	121	<0.01	0.016	147	0.85	0.105	122	0.85
Post-PSVT	0.190*	117	0.04	0.078	144	0.35	0.049	118	0.35
Pre-MRT	0.068	121	0.07	-0.045	147	0.59	-0.027	122	0.59
Post-MRT	0.054	117	0.05	-0.039	144	0.64	0.024	118	0.64

*$p < 0.05$, **$p < 0.01$

RQ 2.3: To what extent does Type of Sketching Instruction predict sketching behavior during a design project course? Second, we looked at the impact of sketching instruction on sketching behavior. The two types of sketching instruction, traditional engineering and sketching in perspective, were compared across the three sketching frequency questions using Mann-Whitney U tests. The results are shown in Table 5.4. The impact of sketching instruction was not significant on any of the sketching behavior questions. Although the question for general sketching frequency (Q1) was only marginally not significant.

Table 5.4: Mann-Whitney U tests of sketching frequency between types of sketching instruction

	Traditional		Perspective						
	M	*Mdn.*	*M*	*Mdn.*	*n*	*U*	*z*	*p*	*r*
General Sketching Frequency	1.48	1	1.86	2	122	1388.5	-1.90	0.057	0.17
Sketching for Prototyping	2.14	2	2.39	3	148	2334.5	-1.19	0.234	0.10
Purposes for Sketching	3.43	4	3.13	3	123	1504.5	-1.26	0.207	0.11

Lastly, I used binary logistic regression to examine how these three independent variables (*RQ 2.1-3:* sketching skills, spatial skills, and sketching instruction) predicted each of the five purposes for sketching (shown in Figure 5.8). Binary logistic regression is used to predict categorical dependent variables from categorical and continuous independent variables (Field, 2013). In this case, I am trying to predict the dependent variable that sketching was or was not used for that particular purpose (e.g., free body diagrams). Logistic regression leverages the independent variables to predict the likelihood of an individual using sketching or not using sketching. The three independent variables shown in Figure 5.8 were analyzed together because we anticipated there may be interactions between the three. For example, a student's initial sketching skills could impact how the sketching instruction impacted their use of sketching on future design projects. For the independent variables, both the pre-sketching instruction and post-sketching instruction measures were included as alternatives, and for spatial skills, both the PSVT:R and the MRT were included in the analysis.

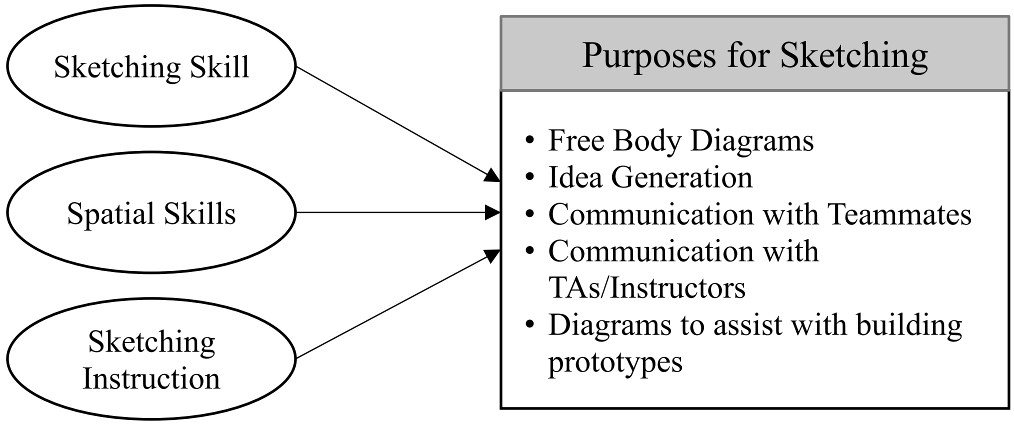


Figure 5.8: Hypothesized binary logistic regression relationships for RQ 2.1-3

A separate binary logistic regression model was analyzed for each of the five individual purposes for sketching. Because I was not sure if all of the independent variables would be a significant predictor, a stepwise forward: likelihood ratio method was used to select which independent variables were included for the model for each sketching purpose. Forward stepwise regression considers individual independent variables in a successive set of analyses. In each step, the most impactful independent variable is included in the model until no more independent variables are significant. Stepwise regression is a simplistic way to down-select significant variables to be included in the final model.

For the present analyses, two of the models were wholly insignificant. None of the independent variables significantly predicted whether or not students would sketch for those two purposes: communication with teammates and communication with TAs/instructors. For the other three sketching purposes (free body diagrams, idea generation, and diagrams to assist with building prototypes), sketching skills were the only construct included in the models. The stepwise progression for each of the three models ended with only one independent variable. The remaining variables for spatial skills and sketching instruction were not significant predictors of any behaviors.

The logistic regression coefficients for the variables included in the models are shown in Table 5.5. The logistic regression model for free body diagrams was significant overall with $\chi^2(1) = 4.12, p = 0.043; R^2 = 0.04\ (Cox\ \&\ Snell),\ 0.05\ (Nagelkerke)$. Pre-sketch skill had a positive relationship with sketching for free body diagrams. The logistic regression model for idea generation was significant overall with $\chi^2(1) = 4.35, p = 0.036; R^2 = 0.04\ (Cox\ \&\ Snell), 0.09\ (Nagelkerke)$. Post-sketching skill had a positive relationship with sketching for idea generation. And lastly, the model for diagrams to assist with building prototypes was significant overall with $\chi^2(1) = 5.18, p = 0.023; R^2 = 0.05\ (Cox\ \&\ Snell),\ 0.07\ (Nagelkerke)$. Pre-sketch skill was a positive predictor of sketching for diagrams to assist with prototypes.

Table 5.5: Stepwise logistic regression of sketching skill, spatial skills, and sketching instruction predicting Q3 specific purposes for sketching – regression coefficients for included variables

Free Body Diagrams

Predictor	*B*	*SE*	*Wald*	*df*	*p*	*Exp(B)*
Pre-Sketch Skill	.086	.044	3.856	1	0.050	1.090

Idea Generation

Predictor	*B*	*SE*	*Wald*	*df*	*p*	*Exp(B)*
Post-Sketch Skill	.186	.094	3.932	1	0.047	1.205

Diagrams to Assist with Building Prototypes

Predictor	*B*	*SE*	*Wald*	*df*	*p*	*Exp(B)*
Pre-Sketch Skill	.103	.047	4.686	1	0.030	1.108

RQ 2.4-2.5: To what extent do Engineering Design Self-Efficacy and Gender predict sketching behavior during a design project course? Data on EDSE and gender were collected in both the sophomore design course and capstone design course. Relationships are examined separately for the two courses in all analyses. First, Spearman's correlations were examined between the EDSE measures and the sketching behavior questions shown in Table 5.6 and Table 5.7. For the sophomore design course, confidence, motivation, and expectation of success were significantly correlated with all questions on sketching frequency. Anxiety had a significant negative correlation only with general sketching frequency (Q1). For the capstone design course, there was only one significant relationship: a positive correlation between motivation and sketching for prototyping (Q2).

Table 5.6: Sophomore Design Course: Spearman's rho correlations of sketching behavior questions vs. EDSE

	General Sketching Frequency			Sketching for Prototyping			Purposes for Sketching		
	r	*n*	*p*	*r*	*n*	*p*	*r*	*n*	*p*
Confidence	0.303**	167	<0.01	0.167**	313	<0.01	0.198**	168	<0.01
Motivation	0.263**	167	<0.01	0.241**	313	<0.01	0.222**	168	<0.01
Expectation of Success	0.328**	167	<0.01	0.193**	313	<0.01	0.244**	168	<0.01
Anxiety	-0.179*	167	0.02	-0.050	313	0.38	-0.139	168	0.07

*$p < 0.05$, **$p < 0.01$

Table 5.7: Capstone Design Course: Spearman's rho correlations of sketching behavior vs. EDSE

	General Sketching Frequency			Sketching for Prototyping			Purposes for Sketching		
	r	*n*	*p*	*r*	*n*	*p*	*r*	*n*	*p*
Confidence	0.021	345	0.69	0.017	348	0.75	0.079	346	0.14
Motivation	0.040	345	0.46	0.176**	348	<0.01	0.022	346	0.68
Expectation of Success	-0.002	345	0.97	0.051	348	0.34	0.040	346	0.46
Anxiety	-0.027	345	0.62	0.031	348	0.56	-0.033	346	0.54

*$p < 0.05$, **$p < 0.01$

Next, I examined the influence of gender on sketching frequency using the Mann-Whitney U-test. The results for the sophomore design course and capstone design course are shown in Table 5.8 and Table 5.9, respectively. There were no significant differences in reported sketching frequency between men and women.

Table 5.8: Sophomore Design Course: Mann-Whitney U tests of sketching frequency between genders

	Female		Male						
	M	*Mdn.*	*M*	*Mdn.*	*n*	*U*	*z*	*p*	*r*
General Sketching Frequency	2.27	2	2.07	2	178	2643.5	-1.07	0.285	0.08
Sketching for Prototyping	2.64	3	2.37	3	344	9024.0	-1.83	0.067	0.10
Purposes for Sketching	3.20	3	3.11	3	179	2818.5	-0.55	0.585	0.04

Table 5.9: Capstone Design Course: Mann-Whitney U tests of sketching frequency between genders

	Female		Male						
	M	*Mdn.*	*M*	*Mdn.*	*n*	*U*	*z*	*p*	*r*
General Sketching Frequency	1.62	1	1.78	2	364	12184.0	-1.39	0.165	0.07
Sketching for Prototyping	2.1	2	2.37	3	369	11809.0	-1.89	0.059	0.10
Purposes for Sketching	3.06	3	3.13	3	365	12793.5	-0.70	0.483	0.04

Lastly, we leveraged binary logistic regression to examine to what extent EDSE and gender predicted sketching for different purposes (shown in Figure 5.9). EDSE and gender were analyzed together because we anticipated potential interactions between the two (e.g., there may be a relationship between engineering design confidence and gender). The logistic analyses were again conducted using forward stepwise regression (likelihood ratio) discussed above. These analyses were conducted separately for the sophomore and the capstone design courses.

In the sophomore design course, two purposes for sketching had no significant predictors: free body diagrams and diagrams to assist with building prototypes. The logistic regression models for these two variables were no significant overall. The remaining three each only had one predictor included in the model. The stepwise procedure again ended after the first variable was included. The coefficients for the independent variables in the significant models are shown in Table 5.10 for the sophomore design course. The model for sketching for idea generation was significant overall with $\chi^2(1) = 16.06, p < 0.001;\ R^2 = 0.09\ (Cox\ \&\ Snell), 0.21 (Nagelkerke)$. Engineering design confidence was a positive significant predictor for sketching for idea generation. The model for sketching to communicate with teammates was significant overall with $\chi^2(1) = 10.59, p = 0.001; R^2 = 0.06\ (Cox\ \&\ Snell),\ 0.15\ (Nagelkerke)$. Anxiety about engineering design was a significant negative predictor of sketching to communicate with teammates (e.g., the more anxious students were the less likely they were to sketch to communicate). Lastly, the model for communication with TAs/instructors was significant overall with $\chi^2(1) = 4.95, p = 0.026; R^2 = 0.03\ (Cox\ \&\ Snell), 0.04\ (Nagelkerke)$. Engineering design motivation was a significant positive predictor of sketching to communicate with TAs or instructors. Gender was not a significant predictor of any of the sketching purposes.

In the capstone design course, logistic models four out of the five sketching purposes were not significant: free body diagrams, idea generation, communication with teammates, and communication with TAs/instructors. The only model that was significant in the capstone course was that of sketching for diagrams to assist with building prototypes with $\chi^2(1) = 5.27, p = 0.022; R^2 = 0.02\ (Cox\ \&\ Snell),\ 0.02\ (Nagelkerke)$.

Engineering design confidence was a significant positive predictor of sketching for diagrams to assist with building prototypes. The coefficients and statistics for the variable in the capstone design course model are shown in Table 5.11.

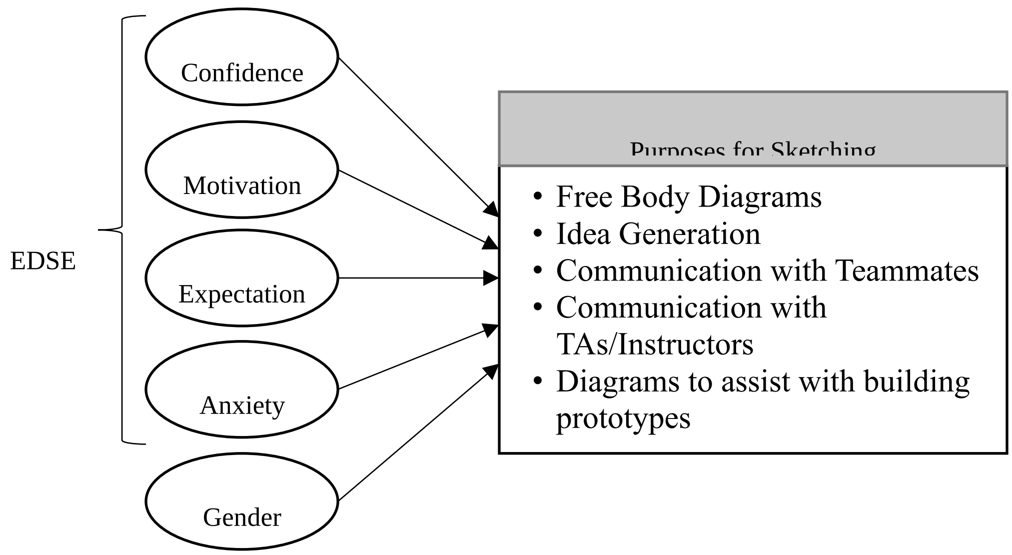


Figure 5.9: Hypothesized binary logistic regression relationships for RQ 2.4-5

Table 5.10: Sophomore Design Course: Logistic regression coefficients for purposes for sketching

Idea Generation

Predictor	*B*	*SE*	*Wald*	*df*	*Sig*	*Exp(B)*
Confidence	.092	.025	13.827	1	<0.001	1.097

Communication with Teammates

Predictor	*B*	*SE*	*Wald*	*df*	*Sig*	*Exp(B)*
Anxiety	-.037	.012	9.357	1	0.002	.964

Communication with TAs/Instructors

Predictor	*B*	*SE*	*Wald*	*df*	*Sig*	*Exp(B)*
Motivation	.030	.014	4.443	1	0.035	1.030

Table 5.11: Capstone Design Course: Logistic regression coefficients for purposes for sketching

Diagrams to Assist with Building Prototypes

Predictor	*B*	*SE*	*Wald*	*df*	*Sig*	*Exp(B)*
Confidence	.021	.009	5.089	1	0.024	1.021

5.4 Discussion

H1: Engineering students' sketching skills have a positive effect on frequency of sketching during a design project. The data partially support the first hypothesis. A positive correlation was observed between sketching skills and the number of purposes sketching was used for, and sketching skills were a predictor for three out of the five different sketching purposes surveyed. Previous work showed a correlation between sketching skills and overall sketching frequency (Yang & Cham, 2007). In the data presented herein, there was not a correlation with general sketching frequency (Table 5.3). Although, our data were collected through self-report instead of observations of design notebooks, and this relationship is likely more easily observed through design notebooks. However, sketching skills were actually associated with specific sketching activities during design (Table 5.5) – free body diagrams, idea generation, and diagrams to assist with building prototypes. It is interesting to note that sketching skills did not predict activities associated with sketching for communication. This lack of relationship suggests that designers sketch to communicate regardless of sketching skills. Sketching skills predicted sketching for free body diagrams, idea generation, and diagrams to assist with prototyping. These relationships suggest that sketching skills may not impact overall sketching frequency, but rather sketching skills might make designers more inclined for some specific sketching behaviors that might be less accessible without this skill.

H2: Students who received two-point perspective sketching instruction sketch more frequently than students who received traditional engineering sketching instruction. The data reject hypothesis two in favor of the null hypothesis. There were no significant relationships between the type of sketching instruction and how frequently students sketched during a capstone design project. Previous work has shown significant increases in sketching skill over the course of perspective sketching instruction (Weaver, Ray, et al., 2022). However, the relationship of behavior with skill was relatively weak, so this may not drive sketching behavior change. Previous research also showed that sketching instruction can reduce sketching inhibition and increase sketching frequency (Booth et al., 2016). However, the reduced inhibition did not hold over time as participants were further from the period of sketching instruction (Booth et al., 2016). The sketching instruction intervention was fairly small – six weeks of instruction in a 3-credit hour course. It is likely that this intervention was too small to have lasting impacts on students' sketching behavior. Perspective sketching techniques should encourage freehand sketching behaviors. Potentially a larger instructional intervention could increase students' use of sketching during design.

H3: Engineering students' spatial visualization skills have a negative effect on frequency of sketching during a design project. The data fail to support hypothesis three. Previous work suggested that students with better visualization skills would lean more on internal representations for design and therefore would sketch less frequently (Yang & Cham, 2007). The data presented here show the opposite may be true. A positive correlation was observed between students' initial spatial visualization skills and their general sketching frequency during design. This suggests that designers may not lean more on higher skills of internal visualization, but rather students may leverage their stronger spatial skills for more fluent external representation. Further work should be done to better understand the interaction between spatial skills and sketching skills.

It is interesting in the case of both the sketching skills and spatial visualization skills that initial measures of these qualities in an entry-level course significantly predicted behavior in a capstone design course an average of six semesters later. Designers' initial skill levels are still impacting their design behavior on future design projects even after much educational intervention. It is critical for engineering educators to understand why this is. It may be that this is just the natural inclination of the designers, or it may be that the engineering designers are not receiving the training on these sort of skills that are critical to design. There may need to be a greater emphasis on the visual thinking and representation aspects of design the way designers reason with design problems in practice.

H4: Engineering Students' engineering design self-efficacy has a positive effect on frequency of sketching during a design project. The data partially support hypothesis four. There were differences in the impact of EDSE on sketching behavior between the two courses. In the sophomore design course, design self-efficacy was a predictor for most behaviors. Students with higher design self-efficacy were more likely to sketch more frequently, to sketch for prototyping, and to use sketching in a larger variety of ways. In the sketching purposes, sophomore design students with higher design self-efficacy were more likely to use sketching for three out of the five sketching purposes. The only relationship found in the capstone design course was that students with higher motivation were more likely to sketch for diagrams to assist with building prototypes. This finding is interesting in that capstone design students had significantly lower design motivation than sophomore design students. Motivation may be a critical thing to monitor in capstone students to understand their design behaviors. These results suggest that design self-efficacy may be much more critical in the early years of education. Early-stage students with higher confidence, higher motivation, and lower anxiety are more likely to sketch to generate concepts and communicate with peers or instructors. Improving students' self-efficacy early on could lead to developing positive design behaviors that could help students out in the long run.

H5: Male and female engineering students will not sketch at a significantly different frequency in design courses. The data fail to support hypothesis five. The previous work on gender differences for sketching behavior was conflicted. In a study of industrial design students, men were found to sketch with higher quality than women (Barnhart & Walters, 2018). However, in the students of engineering students there were conflicting results. A study of design logbooks showed no difference in gender (Song & Agogino, 2004), but a study of idea generation found that women generated more sketches than men (Das et al., 2022). The data presented herein observed no relationship between sketching behavior and gender. Men and women engineering designers were equally likely to generate sketches during design projects.

5.5 Limitations

There are a number of limitations with this study largely associated with the difficult data collection methods spanning across multiple courses over multiple years. It is a major limitation that there was not significant overlap in data between the entry-level design and graphics course and the sophomore design course; it would have been meaningful to see how sketching skills, spatial skills, and sketching instruction influenced design sketching in a more closely timed design course. It is likely that the relationships between these variables would have been stronger if their design behavior was followed in the semester or two after taking the entry-level course instead of the average of six semesters between the data points analyzed. However, this limitation was unavoidable given the timing of data collection. The time between the entry-level course measurements and the capstone design course measurements also limits the power of those relationships. Ideally, it would be beneficial to measure sketching skills, spatial visualization, and sketching behavior all in the same semester in the same course, but that was outside the scope of this study. The time between the two measurements also speaks to the power of the relationships.

It should also be noted that both the sophomore course project and capstone course project are team-based design projects. Team dynamics were not surveyed, and these likely add noise to the study. Different students on the design team may be more or less likely to use sketching for specific purposes given their role on the design team. For instance, a design team lead may be more likely to use sketching for communication but may be less likely to use sketching to assist with building prototypes. These interactions could have been accounted for in the analyses used, which could have provided more clarity on how designer characteristics such as skill and self-efficacy influenced behavior.

5.6 Conclusions

Freehand sketching plays a critical role in engineering design. This chapter has examined more closely the sketching behavior of designers across two engineering design courses. Sketching skills and spatial skills both had a positive correlation with sketching frequency in a capstone design course. Sketching skills were more associated with using sketching for a variety of purposes. Engineering design self-efficacy had a positive correlation with sketching frequency in a sophomore design course. This speaks to the importance of boosting students' confidence early on to help them develop good design habits. Neither gender nor type of sketching instruction had a significant impact on sketching behavior. It is likely that a larger period of sketching instruction could benefit students sketching behavior, but future work is needed to understand how much to prioritize freehand sketching in engineering education. These results provide insights into why designers sketch. Hopefully, these insights can guide future work in improving sketching for engineering sketching and encouraging engineers to sketch.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

The goal of this dissertation was to examine the role that sketching skills play in engineering design and engineering education. I first presented a study exploring methods to improve sketching education for engineering students. Then, I presented two studies looking at how sketching skills and other factors influence idea generation abilities and sketching behavior during design project courses. These studies address the costs of improving sketching skills – the investment in education necessary to see significant gains, and the benefits of sketching skills for engineers – the degree to which sketching skills enhance aspects of the design process. Evaluating the costs and benefits together frames the importance of sketching education for engineers.

6.1 Improving Engineering Freehand Sketching

RQ1: To what extent can engineers' sketching abilities be improved through simple changes in the curriculum? The first study showed that sketching skills can be improved with small investments of only 5 weeks of instruction in sketching education and sketching self-efficacy with only 3 weeks. Teaching sketching techniques that prioritize freehand sketching improves freehand sketching abilities. Perspective sketching gives students additional design tools for visual representation beyond what has traditionally been taught in engineering. And importantly, transitioning sketching education to perspective sketching techniques also supports development of spatial visualization skills, which are critical to student success (Hilton, Gamble, et al., 2018). The amount of instruction is a critical issue that engineering curriculums should consider closely. A small amount of sketching instruction can improve students drawing self-efficacy, which is important for encouraging sketching and reducing inhibition. However, a slightly larger investment in sketching skills can significantly improve students sketching skills. It is encouraging from the perspective of engineering education that you can see significant gains in a critical skill without investing too much time. Lastly, Sketchtivity has some benefits for engineering education. The software automates the sketching evaluation process offloading some of the work of the instructor, and Sketchtivity offered tips and feedback to motivate users to practice. Sketchtivity did not significantly impact sketching skill development, but users were not negatively impacted by practicing on a tablet and paper. More research is needed to better understand the benefits of an intelligent sketch tutoring software in the classroom. In summary, sketching skills and drawing self-efficacy can be improved through adopting freehand sketching curriculums and investing more time in sketching instruction.

6.2 The Role of Sketching skills and Sketch Detail in Idea Generation

RQ2: To what extent do sketching skills predict ideation effectiveness? The second study examined the role of sketching skills and sketch detail (representation, word count, view count, and texture/shading) in idea generation. Sketch detail served as an insightful mediator between sketching skills and ideation effectiveness. Sketching skills related to aspects of sketch detail, and sketch detail corresponded with aspects of ideation effectiveness. Sketching skills only significantly correlated with one of the four sketch detail measures, representation (2D vs. 3D). Two other measures of sketching style (word count and view count) negatively correlated with ideation effectiveness. The disjointed connection with sketch detail offers some explanation as to why sketching skills and ideation were not as strongly connected as I hypothesized. Sketching skills correlated with representation, but representation was independent of ideation effectiveness. While idea generation was much more heavily impacted by sketch detail and how much participants elaborated on their concept descriptions through word count and view count, which were independent of sketching skills. The consistent relationship between generating concepts and elaboration leads to a clear recommendation for early-stage idea generation: be concise in your design descriptions. Over-elaboration poses several threats to productive conceptual design: elaboration can slow you down and you'll produce fewer ideas, it may lead to fixation on a design solution, and if elaboration produces higher quality presentations it could skew the perception of the concept quality. Future work needs to evaluate the impact of elaboration on communication effectiveness.

Sketching skills were largely independent of ideation effectiveness but had a weak positive relationship with quantity after sketching instruction. However, over the course of sketching instruction there were several positive outcomes for idea generation. Over the course of sketch instruction, sketching skills, sketching self-efficacy, and several measures of sketch detail improved. Students used fewer words, they were more likely to sketch in 3D over 2D, and they used texture and shading more frequently. None of these gains associated with improved sketching skills were associated with reduced ideation effectiveness. However, these increased tools of skill, confidence, representation, and shading expand designers' range of sketch detail giving them a broader set of tools to visually represent ideas. Overall, sketching skills and ideation are largely independent or weakly correlated or a greater amount of skill is needed to observe differences in ideation. Designers largely generate and represent similar amounts of ideas regardless of their sketching skills when given a set time limit.

6.3 Predictors of Sketching Behavior

RQ3: To what extent do the following constructs predict sketching behavior during a design project course? (Sketching skills, type of sketching instruction, spatial visualization skills, engineering design self-efficacy, and gender) The final study examined how several factors predicted sketching behavior in engineering design project courses over time. Sketching skills, spatial skills, and design self-efficacy were significant predictors of sketching behavior. The most interesting thing about the relationships was the longevity. Sketching skills and spatial skills evaluated in the first week of an entry-level course significantly correlated with sketching behavior in a senior capstone course. Engineering students' initial skill levels still influenced their sketching behavior on average six semesters later. Even though the relationships were weak, this speaks to the longevity of design behaviors. If students are taught more rigorous sketching skills, then they may have a stronger inclination to sketch that could stick with them in future design projects. There is still a question about the impact of sketching instruction on sketching behavior. In the current study, sketching instruction did not significantly impact designers sketching behaviors on future design projects in measurable ways. Sketching instruction should be extended to the point where it has lasting impacts on students sketching skills and behavior. These long-term benefits would ensure that engineering students were receiving adequate training for design.

6.4 Overall Implications

The three studies taken together have interesting implications for engineering practice and education. If you are a practicing engineering designer, developing your freehand sketching skills can only help you. It does not take excessive time or practice to significantly improve sketching skills, and it takes even less time to improve confidence in drawing abilities. This investment is worth it to increase the use of sketching for exploring design concepts and improve representation and understandability.

For engineering educators, the results presented in this dissertation have meaningful implications. Engineering curriculums need to reevaluate how they prioritize sketching in education. Time is a valuable and scarce resource in engineering undergraduate programs, so the difficulty of allotting resources in noted. However, sketching does not require an overabundance of time to significantly improve students' abilities and confidence. A larger investment in this skill could have large implications for engineering students' design work and sketching behavior. Positive advances have been made in sketching education by adopting perspective sketching techniques and providing a third of a semester of freehand sketching instruction. However, I would argue that universities should consider increasing sketching education because the current curriculum is still not creating lasting changes in sketching behavior. Students' use of sketching was still more connected to their initial sketching and spatial skills than it was to the freehand sketching course. A slightly larger investment in sketching skills could create larger and lasting improvements in students sketching skills and behavior.

Sketching is a powerful tool for engineering design. Many of the benefits of sketching are realized regardless of a designer's sketching skills – designers can generate ideas and communicate with teammates. However, improving sketching skills can benefit design processes resulting in sketching with stronger sketch detail and more understandability (Das et al., 2022) and increasing a designer's inclination for sketching during the design process. Investing in freehand sketching skills has positive implications for engineering designers and engineering education and can be aided by simple techniques and small investments. Future work is still needed to understand many of the implications of sketching skills for design.

6.5 Future Work

The studies presented herein move the needle forward for understanding the role of sketching skills in engineering design and engineering education. However, these studies are not without their limitations, and there is still more to understand about the influence and importance of sketching. In this section, I outline several potential directions for future work. For some of the topics below, research is already underway, but the majority of them are simply the potential highest impact studies from my perspective.

6.5.1 Sketchtivity's Educational Impact

The study presented in this dissertation compared students who used Sketchtivity to those who did not. No differences were observed between the two groups, but at least students' skill development was not deterred by sketching on tablets instead of paper for a time. Further work needs to be done to understand the educational impact of Sketchtivity. Future work will study more closely the benefits of the Sketchtivity feedback. The feedback Sketchtivity provides is the main educational advantage – giving students corrections and advice in real time. This feedback is intended to help students improve their skills more quickly and to motivate them to practice more and score higher on the tasks. Currently a study is underway comparing students using Sketchtivity with and without the feedback. The study will leverage Sketchtivity's precise evaluations of sketches to track students sketching improvement more closely. This study will also track motivation through the number of extra lessons students complete for practice. This study of Sketchtivity feedback should provide a clearer picture of the pedagogical benefit of Sketchtivity.

6.5.2 Dimensions of Sketching Improvement

This dissertation leveraged evaluations of overall sketch quality to track sketching skills. While this measure was effective for tracking progress and comparing skills to other measures in engineering design, it does not tell the full story of sketching skill development. Further work is underway to break down sketch quality for the Sketching Foundations Test into a set of dimensions that describe more specific aspects of sketching skills by students. These dimensions will be used to examine the aspects of sketching skills that are most improving over the course of sketching instruction in entry-level engineering courses. This study of sketch quality dimensions will provide further insight into the extent to which students sketching skills are improving.

6.5.3 Idea Generation Effectiveness of Experienced or Trained Designers

The largest limitation of the sketching skills and idea generation study was that the participants were largely inexperienced engineering students. Experienced designers may behave differently during idea generation, and this, in turn, may affect the relationships between sketching skills and idea generation. Future work looking at a smaller sample of practicing engineering designers would help confirm the results.

Further, the strongest relationships with ideation effectiveness were with word count and view count. Future work could first train students to avoid elaboration in idea generation and train them in the basic rules of brainstorming. Giving students more formal training of idea generation methods and explicitly calling out the elaboration bias could alter the relationships in the study. A study of trained or experienced engineers would provide greater external validity to the results of the study.

6.5.4 Longitudinal Impacts of Rigorous Sketching Instruction

In the study of sketching use in design project courses, sketching instruction was not found to have a significant effect on students sketching behaviors. However, this result was only analyzed in the capstone design course because of limitations in the data collection. Future work should employ a larger sketching instruction intervention and closely track its impacts over time. Understanding the longevity of the sketching skills developed and sketching practices developed in future design projects would provide further insight into the pedagogical importance of sketching instruction. This result needs to be examined at multiple levels of sketching instruction across multiple universities.

6.5.5 Further Design Tasks Impacted by Sketching skills

This dissertation examined how sketching skills predicted idea generation abilities and general use of sketching during the design process. These are not the only tasks designers leverage sketching for. Future work could look at sketching skills in different contexts, such as communication, working memory, and the feedback loop of sketching for decision making. Repeating past protocol studies on sketching and the designers thought processes with systematically strong and weak sketchers could give further insight into the importance of this skill for engineers.

6.5.6 Sketching in Engineering Practice

One of the largest questions in my mind throughout this research was, “does sketching matter in engineering practice?” Broadly, we as researchers should always seek for our research to be applicable. Given the minimal sketching education in some engineering programs, I wondered if engineers in practice were sketching at all or if they wish that sketching was easier. Future work could survey practicing engineers on several topics related to sketching: the amount of sketching training they have, the degree to which they use sketching, the degree to which they wish to use sketching, and their perceived value and purposes of sketching. This survey could account for engineers’ role in the organization, the field they practice in, their level of engineering education, their alma mater, and general demographic factors. This survey study would provide valuable insight into what engineers perceive as desired skills. The survey could also incorporate questions related to many other engineering skills beyond sketching.

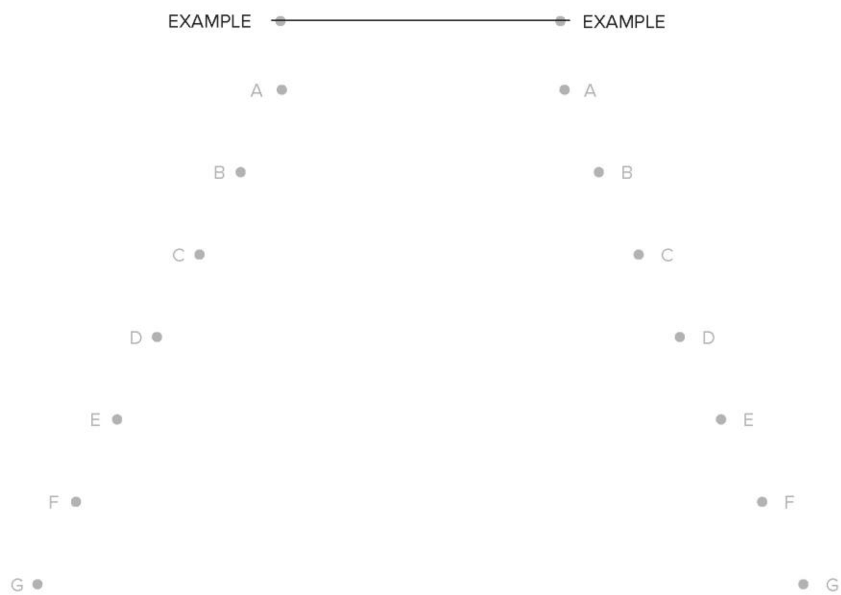
6.5.7 Dispelling Myths of the “Artist”

Over the course of this dissertation, I have spent a good deal of time reviewing sketching literature, observing students improve their sketching behavior, and learning a few sketching skills myself. From these experiences, the single most striking aspect of this topic was the degree to which sketching skills could be learned. When I was an undergraduate engineering student, my opinion of sketching skills was that there were artists and non-artists, and I was a non-artist. I have never been gifted in any craft that could be considered art, and I thought that was the end of it. Understanding the degree to which these skills can be learned in a short amount of time gave me hope that not just me, but any engineer can become an “artist” or a sketcher. The question of identity may be more poignant than sketching skills when it comes to influencing engineers’ sketching behaviors. Future work should look into how students see themselves with regard to sketching and how to influence a students’ sketching identity. What does it take for an individual to identify as an “artist”? I think dispelling this fixed mindset myth that some people are artists, and some are not could have powerful impacts on engineers’ sketching skills and their use of sketching in design.

APPENDIX A. SKETCHING FOUNDATIONS TEST

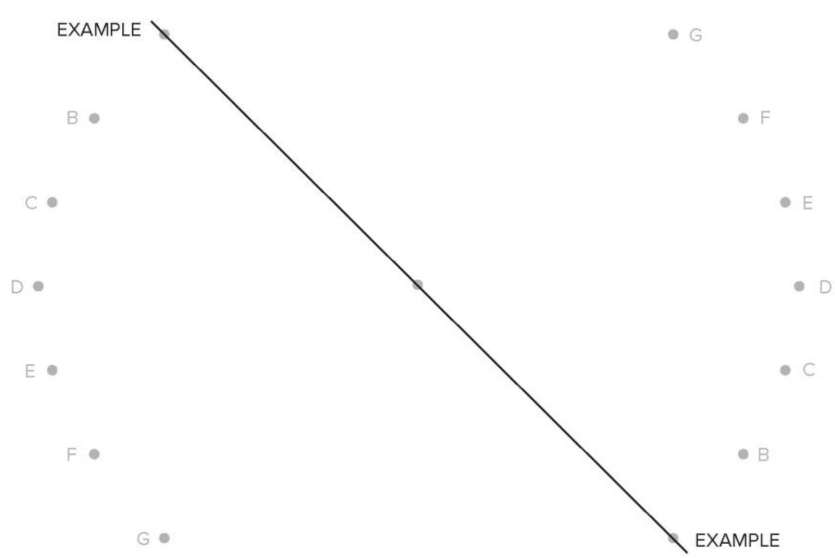
STRAIGHT LINES

Connect the lettered dots with horizontal lines. Sketch quick, confident, continuous lines that do not waver.



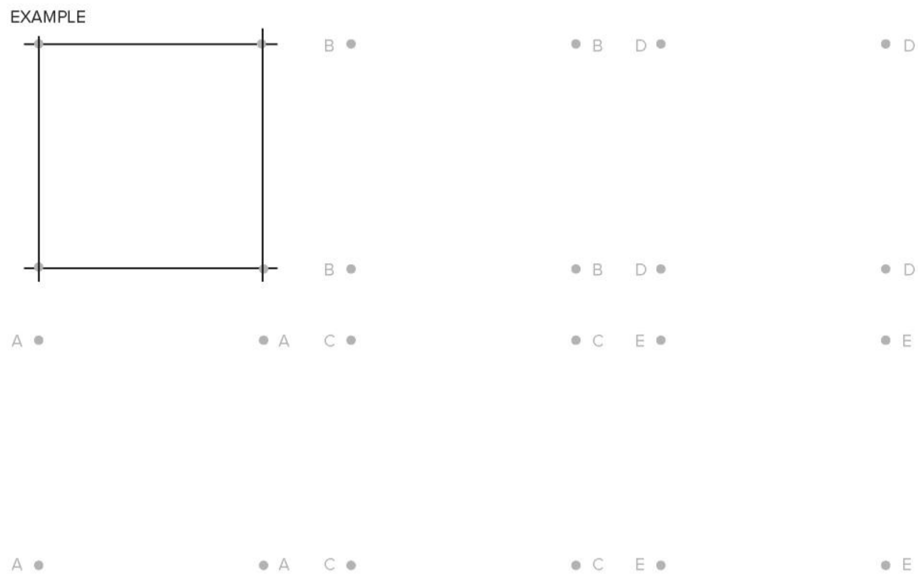
STRAIGHT LINES 2

Connect the lettered dots with crossing lines, being sure to pass through the center point. Make quick confident lines.
Rotate the page to make it easier to sketch the lines.



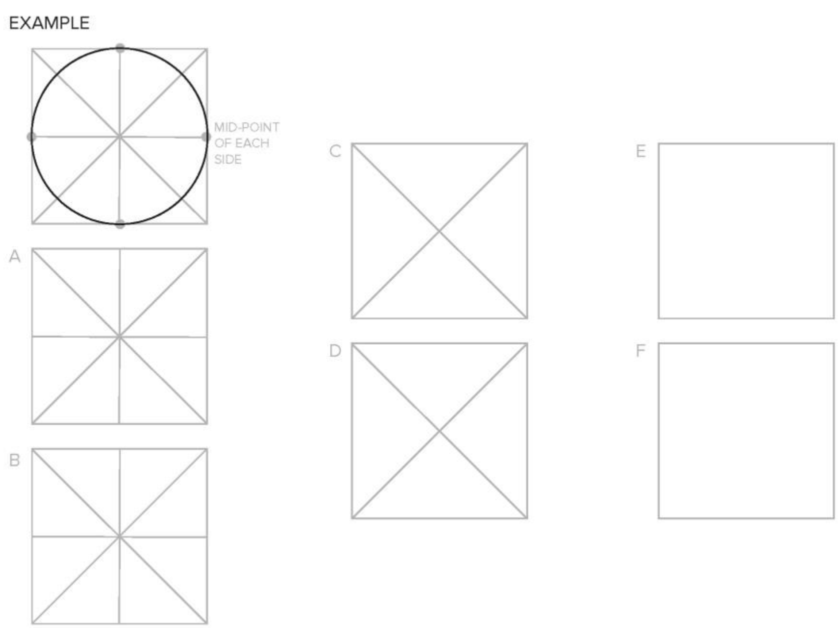
SQUARES

Connect the lettered dots to form squares. Sketch quick, confident, continuous lines that do not waver. Rotate the paper so each line is comfortable.



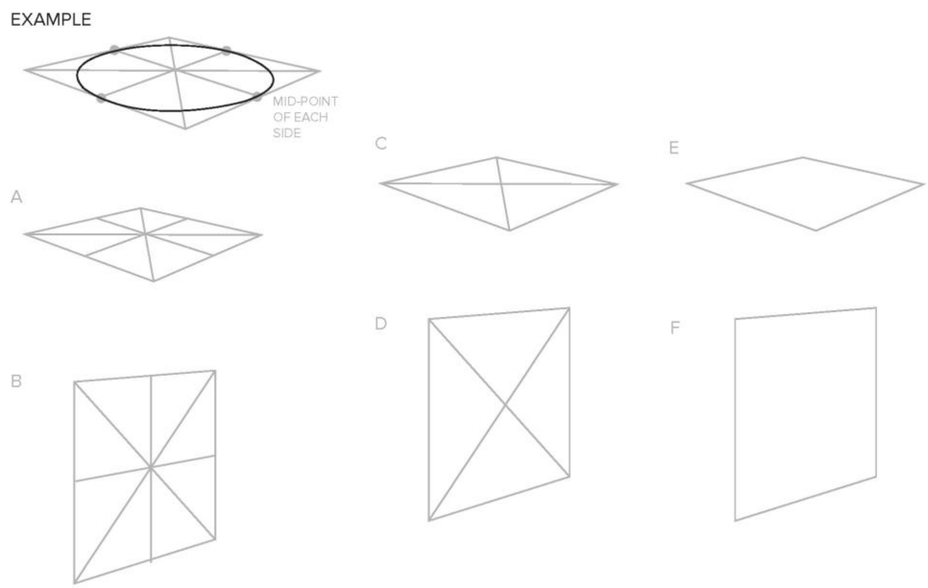
CIRCLES

Sketch circles that fit perfectly inside these squares. It may help to “ghost” the circles before applying pressure.



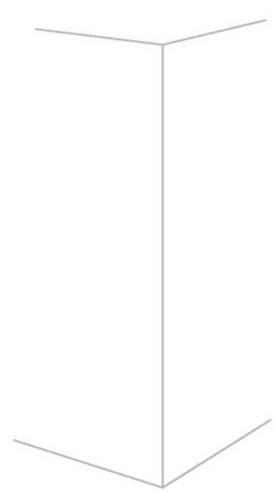
ELLIPSES

Sketch ellipses that fit inside these planes in perspective. It may help to “ghost” the ellipses before applying pressure.



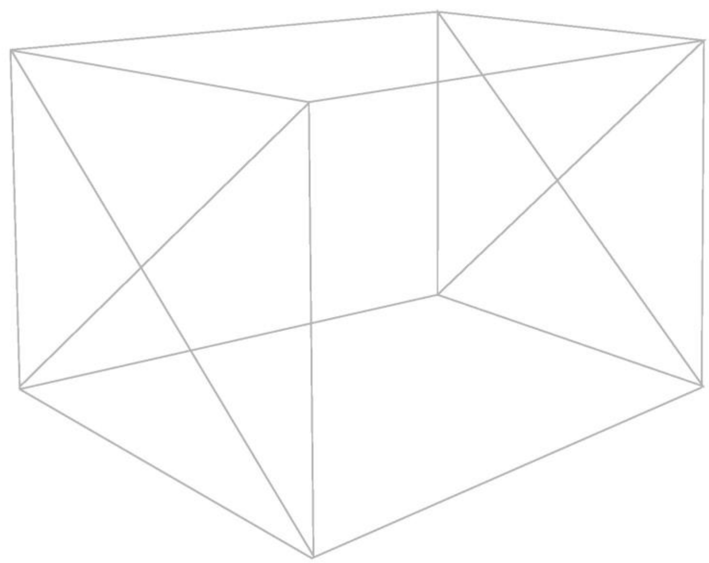
CUBE

Sketch a cube in 2-point perspective using the provided construction lines.
You may use additional light construction lines.



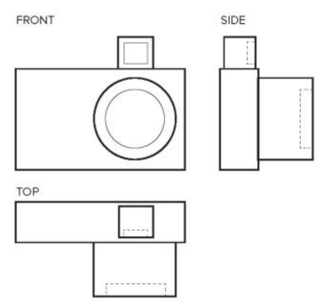
CYLINDER

Sketch a cylinder in 2-point perspective using the provided cylinder construction lines.
You may use additional light construction lines.



CAMERA

Sketch this camera in two-point perspective. Focus on perspective accuracy and realism by making light construction lines first.



APPENDIX B. ENGINEERING DESIGN IDEA GENERATION PROBLEMS

Two idea generation prompts were used in the study in Chapter 4 of this dissertation. The prompts shown below are as they were shown to students.

1. Peanut Sheller Design Prompt
2. Corn Shucker Design Prompt

Design Problem - Device to Shell Peanuts

Problem Description:
In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Please sketch and note (with words) one design solution per page starting on the next page.

Design Problem - **Device to Aid in Shucking Corn**

Problem Description:
Corn is currently the most widely grown crop in the Americas with the United States producing 40% of the world's harvest. An ear of corn has a protective outer covering of leaves, known as the husk, and strands of corn silk threads run between the husk and the kernels. The removal of husk and silk to clean the corn is known as shucking corn. Design a device that quickly and cheaply shucks corn for mass production.

http://www.art-photograph-gallery.com/pictures-of-corn.html

Customer Needs:

- Must remove husk and silk from corn cob with minimal damage to kernels.
- A large quantity of corn must be shucked quickly.
- Must be safe for user
- Low cost.
- Easy to manufacture

Please sketch and note (with words) one design solution per page starting on the next page.

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