International Journal of Engineering Education Vol. 38, No. 6, pp. 1836–1850, 2022
Printed in Great Britain

0949-149X/91 $3.00+0.00

Improving Engineering Sketching Education Through Perspective Techniques and an AI-Based Tutoring Platform*

MORGAN B. WEAVER
Woodruff School of Mechanical Engineering, Georgia Institute of Technology, USA. E-mail: mweaver43@gatech.edu

SAMANTHA RAY
Department of Computer Science and Engineering, Texas A&M University, USA. E-mail: sjr45@tamu.edu

ETHAN CLARK HILTON
Department of Mechanical Engineering, Louisiana Tech University, USA. E-mail: ehilton@latech.edu

DENIS DOROZHKIN
Woodruff School of Mechanical Engineering, Georgia Institute of Technology, USA. E-mail: denis.dorozhkin@me.gatech.edu

KERRIE DOUGLAS
School of Engineering Education, Purdue University, USA. E-mail: douglask@purdue.edu

TRACY HAMMOND
Department of Computer Science and Engineering, Texas A&M University, USA. E-mail: hammond@tamu.edu

JULIE LINSEY
Woodruff School of Mechanical Engineering, Georgia Institute of Technology, USA. E-mail: julie.linsey@me.gatech.edu

Freehand sketching equips engineers to rapidly represent ideas in the design process, but most engineering curriculums fall short of equipping students with adequate sketching skills. This paper is focused on methods to improve engineers' sketching skill through type of instruction, length of instruction, and delivery of and feedback for assignments using Sketchtivity, an intelligent sketch-tutoring software. We answer several key questions for providing better sketching education for engineers. Does perspective training improve freehand drawing ability? Can an intelligent tutoring software improve education outcomes? And how much sketching instruction is necessary for engineers? Analyzing the changes in sketching skill from pre- to post-sketching instruction between different instruction types (n = 116), we found that perspective sketching instruction significantly improved freehand sketching ability compared to traditional engineering sketching methods. When comparing pre to post sketching skill of students using Sketchtivity (n = 135), there was no significant difference in improvement between students using the intelligent tutoring software and those that exclusively practiced on paper – both groups improved equally. However, completing sketching tasks on tablets did not hinder students' skill development even when measured on paper. Future work will more directly explore the influence of Sketchtivity on sketching skill development. Additionally, we found that five weeks of sketching instruction greatly improves sketching skill compared to only three weeks of instruction (n = 108), but both approaches significantly improve sketching self-efficacy. These outcomes support more extensive sketching instruction in engineering classrooms, and changes in instruction type to promote more freehand sketching skills.

Keywords: sketching; freehand sketching; visual communication; engineering curriculum

1. Introduction

The focus of sketching education for engineers is changing. Traditional engineering sketching education focuses on isometric and orthographic views drawn on graph paper or using a straight edge. 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 [1]. 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.

* Accepted 20 June 2022.

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. Perspective drawing's key contribution for engineering is it develops students' freehand sketching abilities with the removal of straight edges and 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. It 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 [2].

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 [3, 4]. 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 [5].

The goal of this paper 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*. We 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 [2, 6]. Preliminary results of the impacts on sketching ability showed that perspective sketching significantly improves freehand sketching skill compared to traditional engineering sketching [7]. This paper 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*. We 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). We 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*. We analyze how much instruction is necessary to significantly improve freehand sketching skill. 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, we compare the improvements in freehand sketching skill between these two different length interventions. From these studies, this paper addresses the following three research questions:

1. To what extent does perspective sketching instruction improve freehand sketching skill?
2. To what extent does an intelligent tutoring system such as Sketchtivity improve freehand sketching skill?
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.

2. Background

Freehand sketching is essential in engineering design as the fundamental form of visual communication [1, 8]. It is used from tasks as rote as drawing free body diagrams to setting up mathematical equations to detailed, technical drawings. Even expert designers still rely on freehand sketching: they can design without sketching for short periods of time but rely on sketching to relieve the mental load of the design task [9]. Sketching aids the designer as a means to externalize design concepts for designers to build on and evaluate their concepts [10]. Not only does this free up mental space to move on to other concepts, but it also provides a visual interface where designers can learn about their concept through visual inspection and gives a framework in which to make further design decisions [11, 12]. Furthermore, sketches also serve as a link to memory to recall earlier designs [13]. Documenting sketches throughout the design process may also help designers recall not only the design concept itself but also the discussions and decisions made around them, which is information that is typically lost in the design process otherwise [14]. These benefits are not limited to just the individual designer. Sketches aid the design team as a whole as well because they are the most effective method for teams to efficiently communicate design ideas [15, 16].

Sketching has been limitedly studied within the context of the design process as a whole. Previous works have looked at the correlation between sketching and design outcomes in short student projects. Yang has examined sketching within the design process largely through design notebooks. They showed that sketching, dimensioned sketching in particular, early on in the design process correlates positively with design outcome [17, 18]. However, with regard to sketching quality, they found no direct connection with design outcomes measured by either grade or project rating [19]. Schutze et al., found that sketching improved design quality compared to designing entirely mentally [20]. Song and Agogino also studied sketching in student design projects and found positive correlations between volume of sketches and 3D sketches with design outcome [21]. Interestingly, though, they found stronger correlations with sketches in the later portions of design, which is the opposite of Yang, who found stronger correlations with sketches in the earlier portions. The impact of sketching in the context of the design process is essential in understanding its value for engineers.

Many studies look at the frequency or function of sketching in the design process, but the quality of sketching also has a large impact on the design process. Intentionally manipulating the sketch quality of a design idea has been shown to alter designers' perceptions of the concept quality and creativity [22, 23]. Concepts that were conveyed through higher quality sketches were evaluated as higher quality and more creative concepts, while the same concept conveyed through lower quality sketches was evaluated as lower quality. This outcome means that a designer's poor sketching skill could limit their potential contributions on a design team: high- and low-quality design concepts can be difficult to distinguish due to poor sketch quality, causing teams to be potentially misled to lower quality concepts. Improving and practicing a skill also leads to easier use of that skill; it is possible that designers with poor sketching skill would benefit twofold by improving their sketching ability. Exemplifying this idea in the classroom setting, Yang and Cham showed that students with greater sketching ability produced more sketches during the design process [19]. They also found a possible link that sketching instruction improved sketching frequency during a design task, but these results were inconclusive. This pattern suggests that greater sketching skill gives designers easier access to sketching as a tool. These studies emphasize the importance not just for sketching in the design process but for higher quality sketching, which supports the case for better and more thorough sketching instruction in engineering programs.

Sketching in education is also extremely valuable. Sketching during note-taking has been shown to improve comprehension compared to taking notes in text only [24, 25]. In engineering education, sketching instruction has been shown to be even more important. Traditional engineering sketching has been shown to be an effective intervention to increase spatial visualization skills [26, 27]. Spatial visualization is a critical skill for engineering student success, and improving this skill improves outcomes for engineering students [28]. Sorby and Veurink showed that improving spatial visualization skills through a sketching intervention improved retention rates for engineers [28]. This effect was particularly present for underrepresented groups in engineering. Sketching is critical in engineering education as a means of engaging and stimulating visual-spatial reasoning. However, this work on student outcomes utilized more traditional engineering sketching practice, which is geared towards improving spatial visualization. So, the question remained, could you glean the same benefits from teaching other sketching techniques? Hilton et al. demonstrated that perspective sketching is as effective at increasing spatial visualization skills as traditional sketching methods [2, 6], and this result is important because perspective sketching can then replace more traditional engineering sketching approaches without losing the critical spatial visualization skills.

Westmoreland et al. demonstrated that senior engineering students have a resistance to sketching in the design process, and the sketching they do is not high quality [29]. This problem speaks to the current state of sketching skill among engineering students and the state of sketching instruction among engineering programs. Students do not inherently understand the value of sketching, but their behavior and attitudes toward sketching are easily changed [30]. Interventions such as sketching assignments, sketching lectures, and touchscreen and stylus technology have helped to encourage sketching among students [31].

To summarize, sketching is vital to engineering design for a large variety of reasons that have been well noted in the literature. Then, why is sketching instruction under-prioritized in engineering education? There is some ambiguity about the importance of improved freehand sketching skill for engineers, such as the lack of evidence connecting sketching skill with better design outcomes [17], and that students continue to succeed and progress through design with low artistic quality sketching [29]. However, we would assert from the literature previously cited that the benefits of improved freehand sketching skills are clear. Design concepts portrayed as poorly drawn sketches can be misinterpreted as less creative and lower quality [22, 23]. This weakness limits the individual designer's contribution and could result in a design team following through with a lower quality concept. Also, designers with greater sketching skill sketch more frequently during the design process [19]. Greater skill gives designers greater confidence and/or easier access to sketching as a tool in the design process, which only serves to improve their effectiveness as designers. Learning to sketch also provides the crucial benefit of improved spatial visualization skills allowing sketch skills to be taught without removing critical skills [2, 6]. These and other skills shown in literature make clear the benefits of advancing sketching education in engineering.

3. Methodology

This paper presents results from three studies on improving sketching ability of engineering students through perspective sketching education. The three studies included in this paper 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.

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. 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 [2]. This paper 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 an undergraduate entry-level engineering design and graphics course in Spring 2021 and 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 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, we 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 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 Fig. 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 Fig. 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

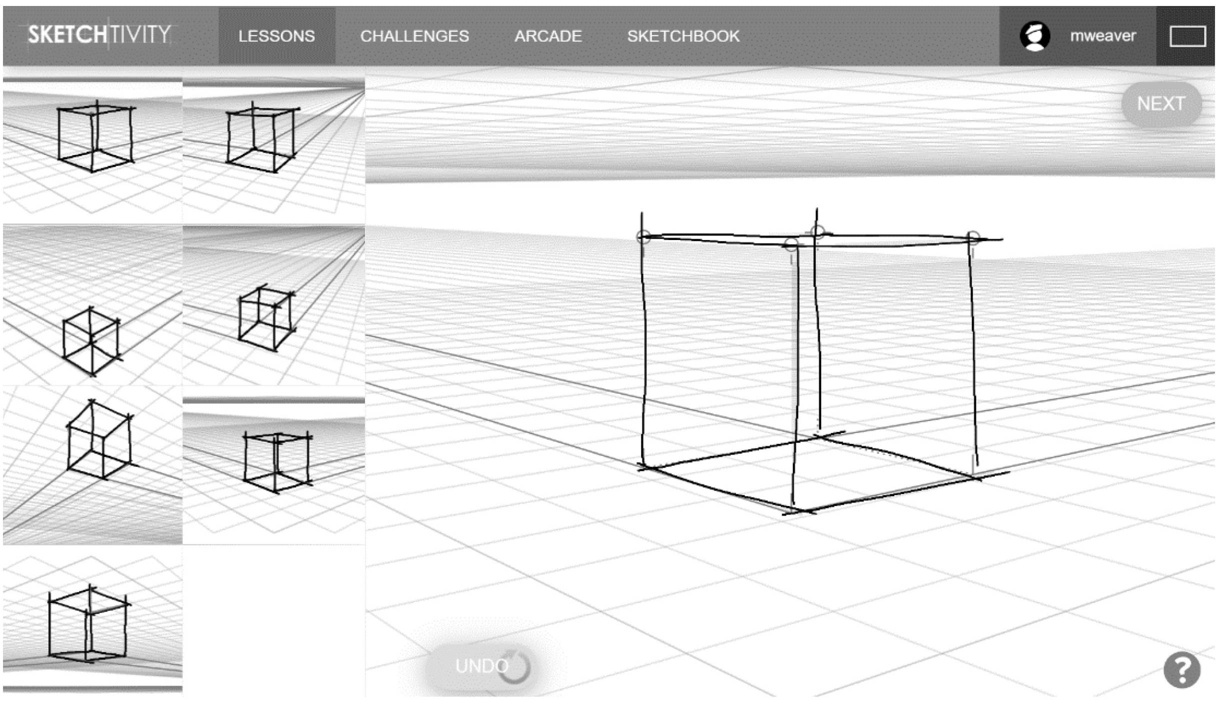

Fig. 1. Sketchtivity Interface – Cube Assignment.

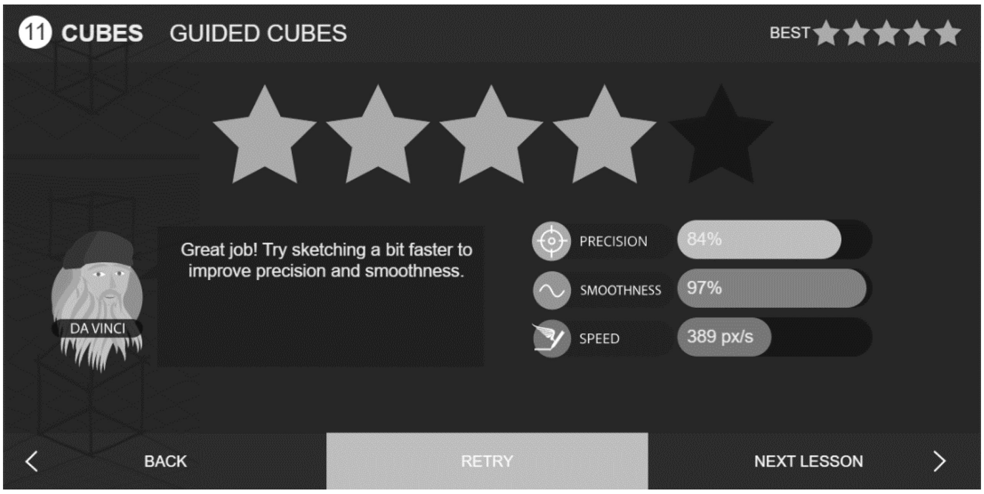

Fig. 2. Sketchtivity Interface – Instructive Feedback.

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.

3.2 Evaluation of Sketching Skill

Students' sketching improvement in the course is evaluated using two tools: the Sketching Foundations Test and Drawing Self-Efficacy Instrument (DSEI) [32]. The Sketching Foundations Test is a series of drawing tasks mostly consisting of primitive shapes in two-point perspective. 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 paper, we focus on the camera exercise. The camera exercise prompt is shown in Fig. 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 paper.

The Sketching Foundations Test is evaluated by expert 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 Fig. 4.

The sketching evaluations in this paper 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

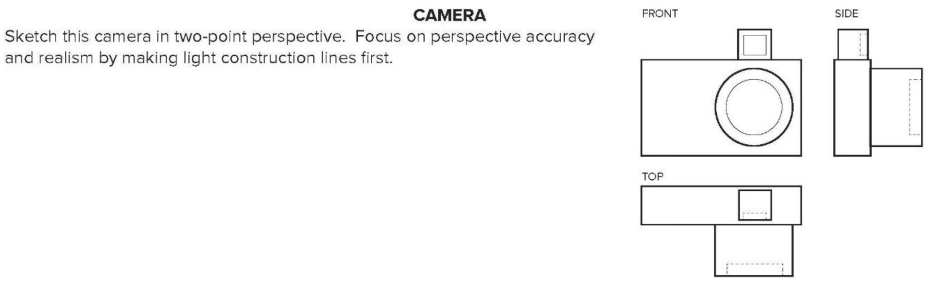

Fig. 3. Sketching Foundations Test – Camera Prompt.

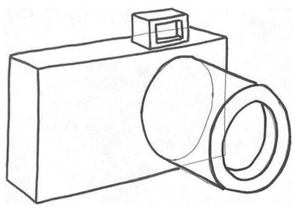

Fig. 4. Sketch Example – Camera.

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 total of n = 505. The final interrater agreement on the full data set was ICC = 0.862. This shows good interrater agreement [33]. The intraclass correlation coefficient used assumed a two-way mixed effects, absolute agreement, and average measures [33]. Both raters evaluated all of the sketches in this study. Therefore, an average of their ratings was used for the analysis in this paper.

3.3 *Drawing Self-Efficacy Instrument*

The Drawing Self-Efficacy Instrument is a validated survey tool consisting of 14 items [32]. 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.

4. Results and Discussion

4.1 *Perspective Study*

RQ1: To what extent does perspective sketching instruction improve freehand sketching skill? The two types of sketching instruction – traditional sketching and perspective sketching – were compared by analyzing the sketching skill of students before and after the instruction period, shown in Fig. 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 [34]. Nonnormality has a "negligible effect" on the Type I error rate of the F-test [35, p. 333]. The results of the ANOVA are displayed in Table 1. 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 $t(51) = 0.962$, $p = 0.341$. The traditional group started at a much higher average sketch quality level than the perspective group but did not improve as dramatically. We are 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. However, we have no reason to believe that this effects the integrity of the results or conclusions.

These data show that the perspective group improved significantly more than the students in the traditional group. The perspective instruction

Table 1. ANOVA Summary Table for 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		

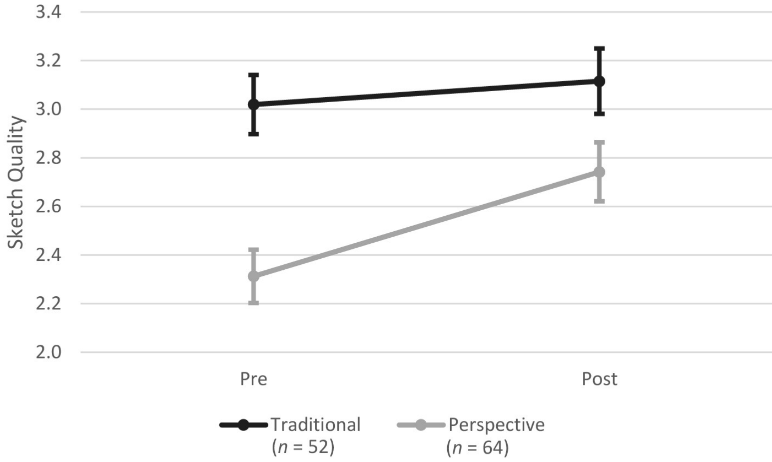

Fig. 5. Differences in sketching improvements between traditional and perspective sketching instruction.

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.

4.2 Software Study

RQ2: To what extent does an intelligent tutoring system such as Sketchtivity improve freehand sketching skill? 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 [34, 35]. The changes in sketch quality scores in the three courses are shown in Fig. 6, and the ANOVA summary table is shown in Table 2. 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 skill. 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 Fig. 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 Uni-

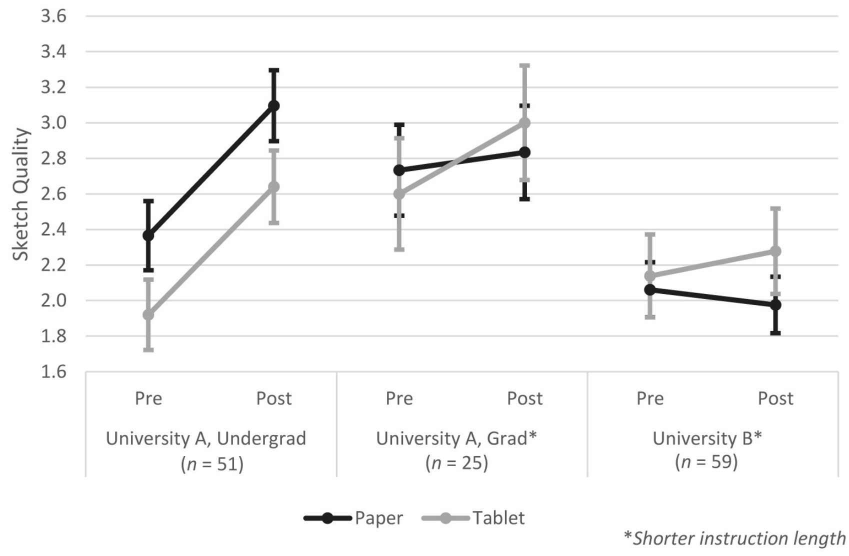

Fig. 6. Improvements in sketch quality in three courses.

Table 2. 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		

versity 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, we can only conclude that Sketchtivity did not significantly negatively impact students' abilities. As a reminder, students completed tests of sketching skill on paper, and the tablet group had to work some on paper and some on a touchscreen with a stylus. Therefore, we have shown that 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. By evaluating students' sketches as they go, the instructors do not have to go back and provide feedback on these assignments.

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 by having all students practice on tablets changing the feedback that the software provides, and by making the Sketchtivity assignments a larger portion of the sketching homework.

We then analyzed the differences in the DSEI scores between the Sketchtivity and paper groups using a three-factor ANOVA displayed in Table 3. The DSEI data did not violate the assumption of normality by a Shapiro-Wilk test. However, Leve-

Table 3. 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		

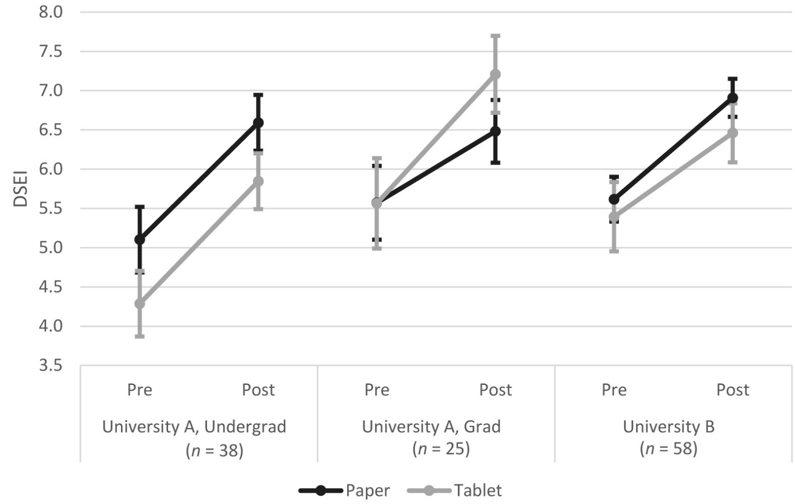

Fig. 7. Similar changes in DSEI for paper and Sketchtivity experiment groups (error bars are +/– S.E.).

ne'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 ($\alpha \approx 0.053$) [35]. Thus, an ANOVA was still used for the analysis. We 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 Fig. 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.

4.3 Instruction Length Study

RQ3: 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? For the instruction length study, we 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 Fig. 8, and the ANOVA summary table is displayed in Table 4. 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 sig-

Table 4. 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		

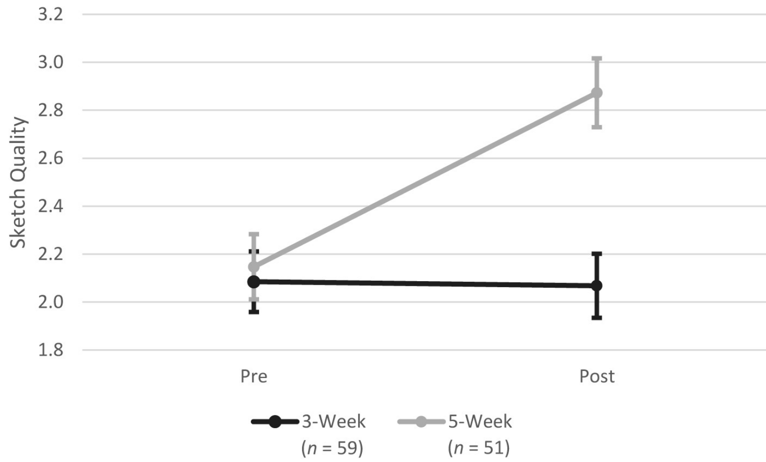

Fig. 8. Differences in improvements in sketching skill between 3-week and 5-week instruction lengths.

nificant 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 Fig. 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 class, not the CAD portion [2], 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 we 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.

We found similar results to the software study with regards to the DSE displayed in Fig. 9 and Table 5. 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 [35]. 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

Table 5. 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		

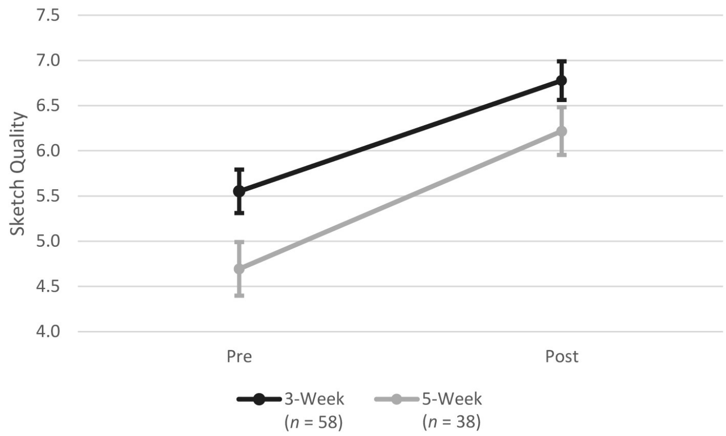

Fig. 9. A 3-week instruction period is adequate for significantly increasing students' Drawing Self-Efficacy Error bars are +/- S.E.

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.

5. 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 [28]. Currently, institutions are underemphasizing this critical skill, 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 paper 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. We found 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, we saw 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. In future work, we will work to specifically measure the impact of the feedback that Sketchtivity provides to gain clearer understanding of the impacts of the software on sketching skill.

We also found 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 be influencing 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, we saw 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, we 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.

Acknowledgements – This work is supported by the National Science Foundation through Award Numbers 2013504, 2013612, 2013575, and 2013554. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

1. D. G. Ullman, S. Wood and D. Craig, The importance of drawing in the mechanical design process, *Computers & graphics*, **14**(2), pp. 263–274, 1990.
2. E. C. Hilton, J. Linsey, W. Li and T. Hammond, Effectively teaching sketching in engineering curricula, *The International Journal of Engineering Education*, **34**(2), pp. 644–652, 2018.
3. W. Li, E. Hilton, T. Hammond and J. Linsey, Persketchtivity: An intelligent pen-based online education platform for sketching instruction, *Electronic Visualisation and the Arts*, pp. 133–141, 2016.
4. B. Williford, P. Taele, T. Nelligan, W. Li, J. Linsey and T. Hammond, Persketchtivity: an intelligent pen-based educational application for design sketching instruction, in *Revolutionizing Education with Digital Ink*: Springer, pp. 115–127, 2016.
5. S. Keshavabhotla, B. Williford, S. Kumar, E. Hilton, P. Taele, W. Li, J. Linsey and T. Hammond, Conquering the cube: learning to sketch primitives in perspective with an intelligent tutoring system, *Proceedings of the Symposium on Sketch-Based Interfaces and Modeling*, 2017.
6. E. C. Hilton, T. Gamble, W. Li, T. Hammond, and J. S. Linsey, Back to basics: sketching, not CAD, is the key to improving essential engineering design skills, *ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2018: American Society of Mechanical Engineers Digital Collection.
7. E. C. Hilton, M. Paige, B. Williford, W. Li, T. Hammond, and J. Linsey, Improving the sketching ability of engineering design students, *DS 87-9 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 9: Design Education, Vancouver, Canada, 21–25.08. 2017*, 2017.
8. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, Engineering design thinking, teaching, and learning, *Journal of Engineering Education,* **94**(1), pp. 103–120, 2005.
9. Z. Bilda, J. S. Gero and T. Purcell, To sketch or not to sketch? That is the question, *Design Studies,* **27**(5), pp. 587–613, 2006.
10. Z. Bilda and J. S. Gero, Does sketching off-load visuo-spatial working memory, *Studying Designers,* **5**(2005), pp. 145–160, 2005.
11. M. Suwa, J. S. Gero and T. Purcell, The roles of sketches in early conceptual design processes, *Proceedings of Twentieth Annual Meeting of the Cognitive Science Society*, 1998: Lawrence Erlbaum Hillsdale, New Jersey.
12. M. Suwa and B. Tversky, What do architects and students perceive in their design sketches? A protocol analysis, *Design Studies*, **18**(4), pp. 385–403, 1997.
13. E. Y.-L. Do, M. D. Gross, B. Neiman and C. Zimring, Intentions in and relations among design drawings, *Design Studies*, **21**(5), pp. 483–503, 2000.
14. S. J. Yen, R. Fruchter and L. J. Leifer, Facilitating tacit knowledge capture and reuse in conceptual design activities, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 1999, vol. 19739: American Society of Mechanical Engineers.
15. G. Goldschmidt, To see eye to eye: the role of visual representations in building shared mental models in design teams, *CoDesign*, **3**(1), pp. 43–50, 2007.
16. J. J. Shah, N. Vargas-Hernandez, J. D. Summers and S. Kulkarni, Collaborative Sketching (C-Sketch) – An idea generation technique for engineering design, *The Journal of Creative Behavior*, **35**(3), pp. 168–198, 2001.
17. M. C. Yang, Observations on concept generation and sketching in engineering design, *Research in Engineering Design*, **20**(1), pp. 1–11, 2009.
18. M. C. Yang, Concept generation and sketching: Correlations with design outcome, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, **37017**, 2003.
19. M. C. Yang and J. G. Cham, An analysis of sketching skill and its role in early stage engineering design, *Journal of Mechanical Design*, **129**, pp. 476–482, 2007.
20. M. Schütze, P. Sachse and A. Römer, Support value of sketching in the design process, *Research in Engineering Design*, **14**(2), pp. 89–97, 2003.
21. S. Song and A. M. Agogino, Insights on designers' sketching activities in new product design teams, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, **46962**, 2004.
22. B. Kudrowitz, P. Te and D. Wallace, The influence of sketch quality on perception of product-idea creativity, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **26**(3), pp. 267–279, 2012.
23. J. Kwon and B. Kudrowitz, The Sketch Quality Bias: Evaluating Descriptions of Product Ideas With and Without Visuals, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, **59278**, 2019 American Society of Mechanical Engineers.

24. A. Schmeck, R. E. Mayer, M. Opfermann, V. Pfeiffer and D. Leutner, Drawing pictures during learning from scientific text: Testing the generative drawing effect and the prognostic drawing effect, *Contemporary Educational Psychology*, **39**(4), pp. 275–286, 2014.
25. J. D. Gobert and J. J. Clement, Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics, *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, **36**(1), pp. 39–53, 1999.
26. S. A. Sorby, Educational research in developing 3-D spatial skills for engineering students, *International Journal of Science Education,* **31**(3), pp. 459–480, 2009.
27. S. Olkun, Making connections: Improving spatial abilities with engineering drawing activities, *International Journal of Mathematics Teaching and Learning*, **3**(1), pp. 1–10, 2003.
28. S. A. Sorby and N. Veurink, Long-term results from spatial skills intervention among first-year engineering students, *Proceedings of the 65th Midyear Meeting of the Engineering Design Graphics Division of ASEE*, 2010.
29. S. Westmoreland, A. Ruocco and L. Schmidt, Analysis of capstone design reports: Visual representations, *Journal of Mechanical Design*, **133**(5), 2011.
30. A. Ruocco, S. Westmoreland and L. C. Schmidt, Sketching in design: easily influencing behavior, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 49057, 2009.
31. L. C. Schmidt, N. V. Hernandez and A. L. Ruocco, Research on encouraging sketching in engineering design, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AI EDAM,* **26**(3), p. 303, 2012.
32. D. Jaison, H. E. Merzdorf, B. Williford, L. L. A. White, K. Douglas, K. Watson and T. Hammond, Assessing Drawing Self-Efficacy: A Validation Study Using Exploratory Factor Analysis (EFA) for the Drawing Self-Efficacy Instrument (DSEI), *American Society for Engineering Education Annual Conference*, Long Beach, California, 2021 in press.
33. T. K. Koo and M. Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, *Journal of Chiropractic Medicine*, **15**(2), pp. 155–163, 2016.
34. G. V. Glass, P. D. Peckham and J. R. Sanders, Consequences of failure to meet assumptions underlying the fixed effects analyses of variance and covariance, *Review of Educational Research,* **42**(3), pp. 237–288, 1972.
35. M. R. Harwell, E. N. Rubinstein, W. S. Hayes and C. C. Olds, Summarizing Monte Carlo results in methodological research: The one-and two-factor fixed effects ANOVA cases, *Journal of Educational Statistics*, **17**(4), pp. 315–339, 1992.

Morgan B. Weaver is a PhD student in the Woodruff School of Mechanical Engineering at Georgia Institute of Technology with a Master of Science in Mechanical Engineering from LeTourneau University. His research focus is design theory and methodology with a specific concentration on early-stage design, concept generation, and creativity in the design process. His current research has an emphasis on engineering education investigating the used of freehand sketching in design and the impacts of makerspaces on university campuses.

Samantha Ray is a PhD student and intelligent user interface researcher in the Sketch Recognition Lab under Director Tracy Hammond at Texas A&M University. She received a BS in Computer Engineering from Texas A&M University in 2018. Her research focuses on human-AI collaboration, developing systems that understand human behavior. She currently works on sketch recognition systems that aid students in STEM fields develop their visual communication and spatial skills with instructor-like feedback. Other projects she has worked on include human activity recognition (HAR) system for promoting healthy habits by recognizing the performance of activities of daily living (ADLs).

Ethan Clark Hilton, PhD is an assistant professor of Mechanical Engineering at Louisiana Tech University in Ruston, LA, where he has been since September 2019 after receiving his PhD from the Georgia Institute of Technology. Dr. Hilton's work focuses on Engineering Design and Engineering Education, focusing on design methodology, project-based learning, and hands-on learning in informal environments. He has also worked on Broadening Participation in STEM through studying barriers in and throughout Engineering curricula for underrepresented groups. He is a member of Louisiana Tech's Integrated STEM Education Research Center (ISERC) and has assisted in the development and implementation of numerous course projects throughout the College of Engineering and Science. He has a passion for making engineering design accessible to all by providing hands-on opportunities to connect engineering theory to tangible design problems and reducing barriers for students from any background to see the need for their perspective in any design problem.

Denis Dorozhkin, PhD, is a Lecturer in the George W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technology, where he teaches courses on engineering graphics and computer-aided design. His research focuses on using virtual reality and haptic interfaces in engineering design, manufacturing, and medical training. He received his PhD in Mechanical Engineering from Iowa State University in 2011.

Kerrie Douglas, PhD is an Assistant Professor of Engineering Education at Purdue and leads the SEED research lab. She studies how to improve the quality of classroom assessments and evaluation of online learning in a variety of engineering education contexts. She was a FutureLearn Research Fellow from 2017–2019; a 2018 recipient of the FIE New Faculty Fellow Award and the 2021 Program Chair for the Educational Research Methods Division of ASEE. In 2021, she received the NSF CAREER award to support her research on increasing the fairness of assessments in diverse engineering classrooms. She holds a PhD in Educational Psychology from Purdue University and Master's in Educational Studies.

Tracy Hammond, PhD is the Director of the Sketch Recognition Lab, Director for the Institute of Engineering Education and Innovation, and Professor of Computer Science and Engineering at Texas A&M University. Dr. Hammond is an international leader in sketch recognition and human-computer interaction research. Her sketch recognition research has been funded by NSF, DARPA, Google, Microsoft, and many others, totaling over 9 million dollars in peer reviewed funding. She holds a PhD in Computer Science and FTO (Finance Technology Option) from MIT, and four degrees from Columbia University: an MS in Anthropology, an MS in Computer Science, a BA in Mathematics, and a BS in Applied Mathematics.

Julie S. Linsey, PhD is a Professor in the George W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technological. Her research area is design cognition, including systematic methods and tools for innovative design with a particular focus on concept generation and design-by-analogy. She also works on design methods, theory, and engineering education. The goal of Dr. Linsey's research is to discover new knowledge about how engineers think and leverage this knowledge into design methods and engineering education. Her current work includes quantifying the impact of university maker spaces, determining the impact of AI sketch recognition tutoring system on Statics students, and identifying how learning to free-hand sketch facilitates improvements to spatial visualization. She has authored over 150 technical publications including over forty journal papers, six book chapters, and she holds two patents.