Title: Teaching Engineering Students Free-hand Sketching with an Intelligent Tutoring System

Short Title: Teaching Engineers Sketching with an ITS

Author Names: Ethan Hilton, Blake Williford, Wayne Li, Tracy Hammond, Julie Linsey

Short Author List: Hilton et al.

Author Affiliations:

Ethan Hilton: Georgia Institute of Technology, 801 Ferst Drive, Atlanta, GA, 30313, USA, ethan.clark.hilton@gmail.com, (318)548-1671
Blake Williford: Texas A&M University, 710 Ross St, College Station, TX, 77843, USA, bwilliford@gmail.com
Wayne Li: Georgia Institute of Technology, 247 4th St. NW, Atlanta, GA, 30332, USA, wayne.li@design.gatech.edu
Tracy Hammond: Texas A&M University, 710 Ross St, College Station, TX, 77843, USA, thammond@gmail.com
Julie Linsey: Georgia Institute of Technology, 801 Ferst Drive, Atlanta, GA, 30313, USA, julie.linsey@me.gatech.edu, (404)385-0106

Contact Author: Ethan Hilton

Abstract

Sketching is an essential skill in engineering design. However, the instruction of sketching in engineering curriculum has greatly diminished in recent decades. Previous studies have shown that teaching an Industrial Design-inspired version of free hand sketching is effective in engineering courses, but engineering professors are often untrained to teach this method effectively. This paper studies the effect of supplementing instructor-taught sketching with an online sketching tutor that utilizes artificial intelligence to provide human-like feedback to user sketches. To measure the impact of the introduction of this program, the authors compared students who used the online tutor against students who only completed paper-based sketching homework using pre- and post-course spatial visualization evaluations and sketching quizzes. The results show that the students using the online tutor significantly improve their spatial visualization skills at a level equivalent to students who had more practice with pen-and-paper sketching.

1. Introduction

Engineers use hand-drawn sketches in a variety of contexts. They are a key component of the language of engineering design (Dym, Agogino, Eris, Frey, & Leifer, 2005) and an integral part of the engineering design process (Ullman, Wood, & Craig, 1990). Sketching has been found to improve communication in collaborative design (Goldschmidt, 2007; Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001). Using sketches is also an effective means of working through a design problem as sketching has been found to improve conceptual understanding of a subject (Gobert & Clement, 1999), aid in understanding ill-defined problems (Cross & Roy, 1989), and assist in the idea-generation phase of product development (Yang, 2009). Sketching is even a proven method for improving spatial visualization skills, a key skill in engineering (Olkun, 2003; Sorby, 2009). Despite all of these findings, instruction in sketching has been given less emphasis as computer-aided design (CAD) programs have become more prevalent (Dym et al., 2005). Teaching students sketching techniques helps to remove their inhibition to using sketching (Booth, Taborda, Ramani, & Reid, 2016). For this reason, an Introduction to Engineering Graphics (IEG) course at Georgia Tech has been redesigned in recent years to incorporate pedagogy for teaching sketching based on methods typically found in Industrial Design curricula (Hilton, Li, et al., 2016).

Introduction to Engineering Graphics consists of five weeks of instruction in sketching while the remaining twelve weeks of the semester focuses on teaching students solid modeling. Before the redesign of the sketching portion of the course, students learned a more traditional version of engineering drawing. This version of the course is referred to as the Traditional version for the remainder of the paper. The Traditional version takes an approach to teaching engineering drawing more commonly found in engineering curricula. Students learn basic drafting techniques using straight edges and grid paper to guide their drawings. The primary objective of the sketching portion of the Traditional version is to prepare students to use CAD programs to generate renderings of a product idea and to improve their spatial visualization skills. After the redesign, three of the four instructors of the IEG course taught the sketching portion using the pedagogy inspired by Industrial Design. This method is referred to as the Perspective version for the remainder of the paper. The Perspective method of the course teaches students to generate realistic renderings of a product via sketch before using a CAD program. Students learned more advanced sketching techniques such as sketching in perspective views, shading, and raytracing to generate realistic depth and shadows. Figure 1 is an example of a student's final sketching assignment.

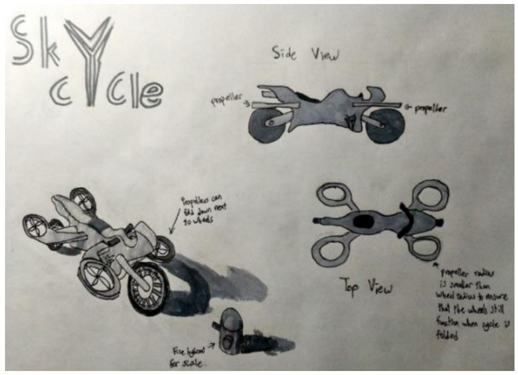

Figure 1. Student work from Perspective version of IEG course

Teaching this method is difficult in engineering curricula as there is a lack of expertise in this pedagogy amongst engineering faculty. The amount of time needed to grade these types of sketches and provide feedback to students is also higher than more traditional methods. This led to the development of SketchTivity, a web-based intelligent tutoring system (ITS) that utilizes pen and tablet technology to teach students sketching through a series of sketching exercises with feedback. The goal of this program is to enhance the sketching ability of students with less instructor interaction.

2. Previous Work

Since the introduction of the Perspective method, there have been several studies on the effectiveness of the new method and ways to continue improving the sketching portion of the IEG course. These studies include looking at the impact of the Perspective method on engineering students and the development of a tool to teach students perspective sketching with less interaction from an instructor.

2.1 Evaluating the Impact of the Perspective Method

In a previous study, researchers studied the Traditional and Perspective methods to determine the impact of teaching engineering students with the Industrial Design-based pedagogy by comparing students taught each version of the course in various key skills including spatial visualization (Hilton, Li, et al., 2016) and sketching ability (Hilton, Williford, et al., 2017). The first study used the Purdue Spatial Visualization Test of Rotations (PSVT:R) to evaluate the students' spatial visualization skills both before and after taking the course (Bodner & Guay, 1997). The study found the Traditional and Perspective methods impacted students' spatial visualization equally. Both methods significantly improved students' spatial skills, especially for those students initially categorized as having low spatial visualization skills. Figure 2 shows the pre-to-post course improvements of students with initially low spatial visualization skills. The second study found that the Perspective method was significantly more likely to improve students' sketching ability than the Traditional Method. Ultimately, these previous studies by Hilton, et al., show that the Perspective method allows students to learn additional skills in the same timeframe while maintaining the development of key skills gained from the Traditional method (Hilton, Paige, et al., 2017).

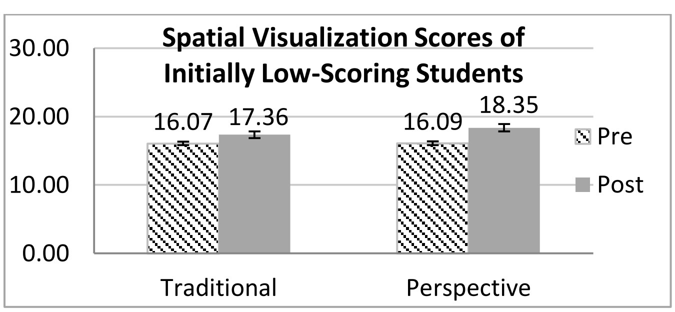

Figure 2. Pre-to-post comparison of PSVT scores of initially low-scoring students

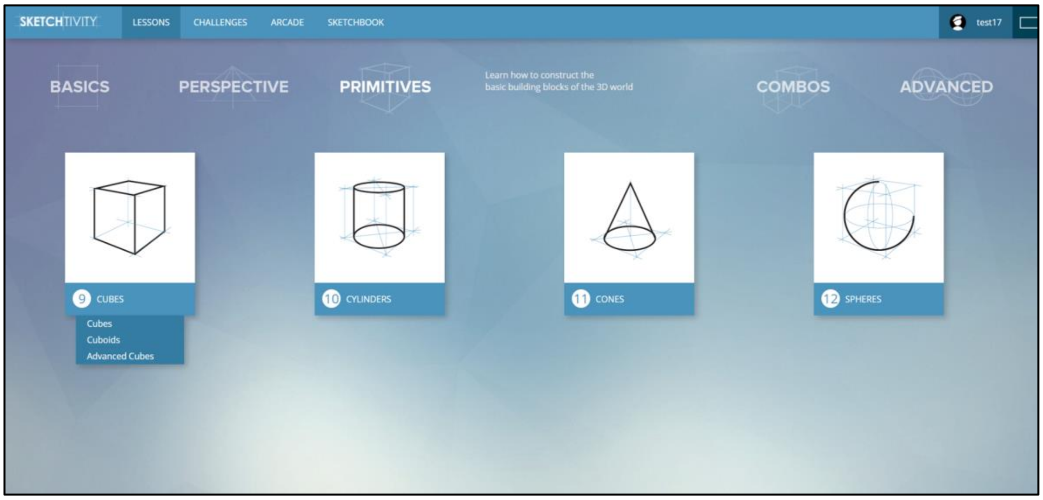

Figure 3. SketchTivity Straight Line Exercise

2.2 SketchTivity

SketchTivity is a web-based intelligent tutoring system that utilizes pen-and-tablet technology to teach students perspective-based sketching through a mastery-based pedagogy (Williford et al., 2016). The system is broken into several modules that allow users to master simple skills such as drawing consistent straight lines and more advanced exercises such as sketching primitives in perspective space (Keshavabhotla et al., 2017). Figure 3 shows the SketchTivity lesson overview for primitive shapes.

SketchTivity provides immediate feedback to users on the accuracy of their lines through colored lines indicating where the line was intended to be drawn versus where the user drew the line. After completing eight exercises, the system provides additional feedback to the user indicating their average accuracy, line quality (smoothness) and speed when completing the exercises.

At the time of this study, SketchTivity included modules on Basic, Perspective, and Primitive Lessons. The Basic lessons included straight and curved lines, squares, and circles. The Perspective lessons included planes and ellipses. The Primitive lessons included Cubes and Cuboids. As the user advances through the lessons, the system provides progressively less scaffolding. Figure 4 shows an example from three different levels of the circle exercise with full, some, and no scaffolding.

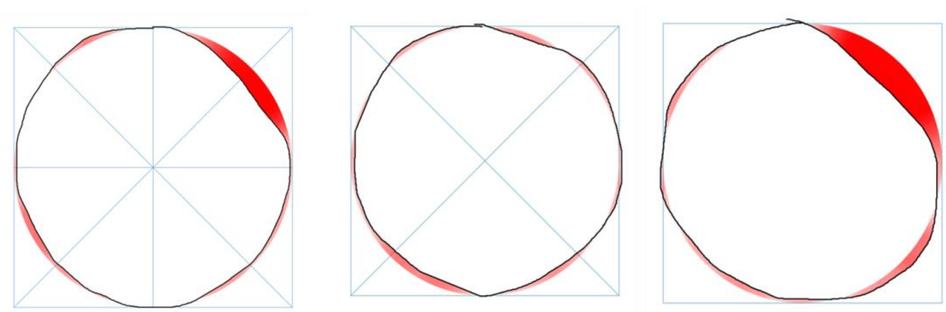

Figure 4. Example of Circle Exercise with Progressively Less Scaffolding

3. Research Question

Researchers observed the Perspective method to be an effective way to teach engineering students sketching. With the development and implementation of SketchTivity into the Perspective version of the course, there is interest in determining the impact of using the system on the user's sketching ability. This paper explores the impact of SketchTivity with the following research question:

Does using an online sketching tutor influence spatial visualization and sketching skills gained by students?

4. Methodology of Evaluation

One instructor implemented SketchTivity into one section of the Introduction to Engineering Graphics course taught using the Perspective method over two semesters. The IEG course consists of two 50-minute lecture periods and one 3-hour lab period each week. The entire class had the opportunity to participate in a study on using a new method of teaching sketching. A random selection of the students who agreed to participate in the study determined 20 students to use the SketchTivity program, and the remaining participants only completed assignments using pen and paper and made up the Paper group. All students who agreed to participate received compensation in the form of extra credit in the course. During three of the weekly lab periods, the students in the SketchTivity group went to a touchscreen monitor lab and completed the modules of SketchTivity that aligned with that week's lecture and sketching assignment. The students in the Paper group remained in the regular lab space with the Graduate Teaching Assistants for the course where they worked on the sketching assignments. The SketchTivity group was also compared to students in the Traditional group who were taught the more traditional version of engineering drawing.

Three of the five sketching assignments for the Perspective version of the course consisted of two parts: exploration and final composition. The exploration involved sketching at least 25 views of the primitives (cubes, spheres, etc.) in two-point perspective (Figure 5). The final composition was a single sketch using all of the skills taught in class. The students in the SketchTivity group did not complete the exploration portion of the assignment but instead performed the equivalent exercise in the SketchTivity program (see Figure 6) at least 25 times. The students received no human feedback on the portion of the assignment completed in SketchTivity.

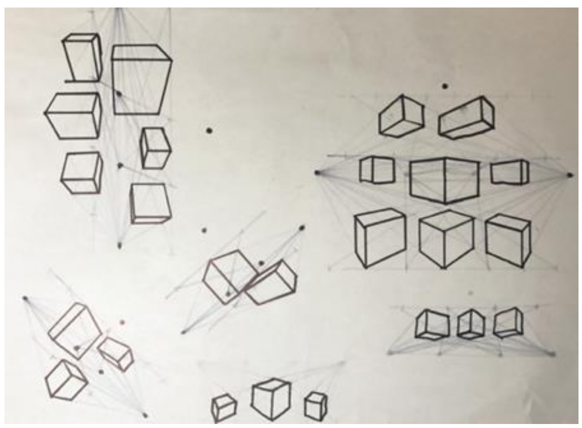

Figure 5. Example of Student Cube Exploration Submission

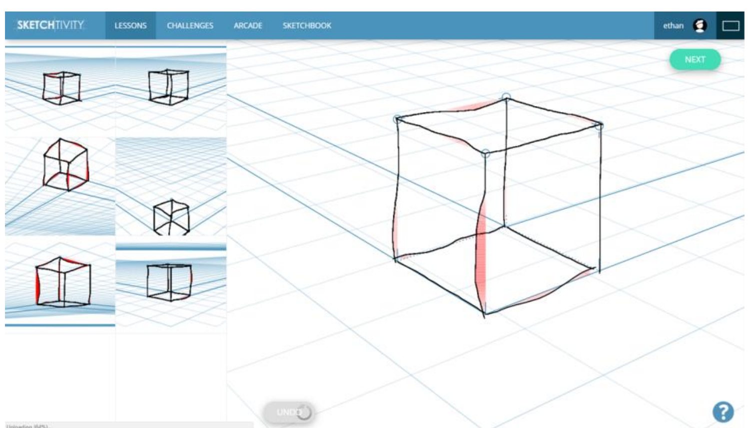

Figure 6. Example of SketchTivity Alternate Assignment

4.1 Spatial Visualization

In order to determine the impact of the system on the students' spatial visualization skills, the students completed a pre- and post-course evaluation. The evaluation used was the Mental Rotation Test (MRT) developed by Vandenberg and Kuse (1978) and revised by Peters, Lehmann, Takahira, Takeuchi, and Jordan (2006). The evaluation consisted of 24 questions with a 12-minute time limit. Over the two semesters, the authors collected and analyzed spatial visualization data from 32 students in the SketchTivity group and 42 students in the Control group. The authors analyzed the results of the pre-course evaluation between the two groups to ensure they were initially equivalent and again at the end of the semester to determine if there was a significant change between the two groups.

4.2 Sketching Ability

To evaluate the students' sketching ability and the impact using SketchTivity had on their development, the students completed pre- and post-course sketching quizzes developed. This sketching evaluation quiz was developed in a previous study (Hilton, Williford, et al., 2016). The final task in this quiz is to draw a camera in two-point perspective given three face views of the camera (see Figure 7). To evaluate whether or not a student improved in sketching ability, researchers scanned the pre- and post-course camera exercises of each student uploaded the scans to an online survey presented to two raters. The raters evaluated each student's pre- and post-course sketch by observing two sketches similar to Figure 7 and which sketch they considered better and if it was slightly better or much better. The order of the students and sketches were randomized to avoid a bias towards the students' group and to which sketch was the pre- or post-course sketch. These raters were instructors or graduate students with experience teaching sketching in engineering. For this study, the authors analyzed sketching data from only one semester (the first of the two semesters mentioned in section 4.1). The analyzed data consisted of 31 students taught the Traditional form of sketching, 16 students in the SketchTivity group, and 26 students in the Control group. To ensure inter-rater reliability, the authors compared the ratings of the two raters. The authors compared the improvement rates between the SketchTivity and Control groups (both taught using the Perspective method) to determine if using SketchTivity was as effective at improving sketching ability as only completing pen-and-paper sketching assignments. The authors also compared the SketchTivity group to the students taught the Traditional method to determine if using SketchTivity to teach the Perspective method still improved sketching ability at a higher rate than the Traditional method.

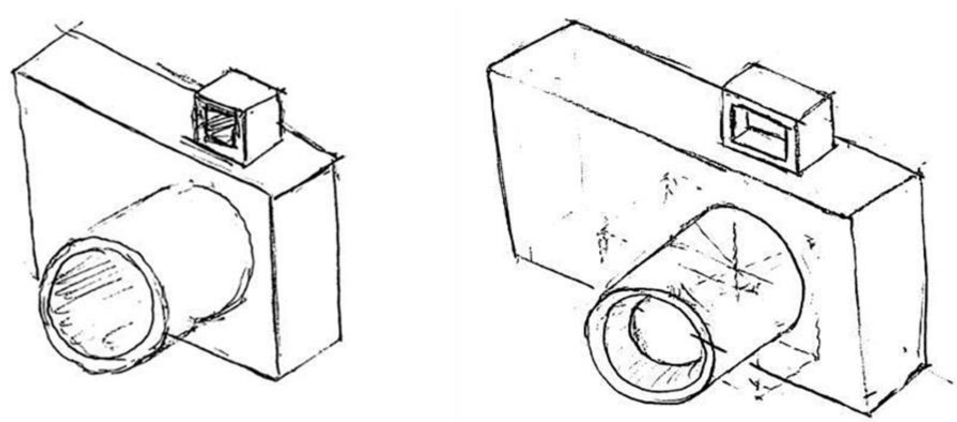

Figure 7. Example of Student Pre- and Post-Course Sketching Quiz

5. Results

The authors conducted between-subject analyses to compare the differences in impact to spatial visualization skills between the SketchTivity group and the Control group. The authors also conducted within-subject analyses to determine whether or not each group improved significantly. The authors conducted between-subject analyses of sketching ability between students from the Traditional Group and the SketchTivity group and between students in the SketchTivity Group and the Control group to understand how SketchTivity compared to both styles of teaching sketching.

5.1 Spatial Visualization Results

The results of the MRT for the pre- and post-course evaluations for each group can be seen in Figure 8. To determine if the groups were initially equivalent, a t-test was run between the two groups resulting in a p-value of 0.56 (t= -0.59, df=78). This indicates that the two groups were not significantly different initially ($\alpha = 0.05$). The groups were also compared using a t-test on the post-course evaluations which resulted in a p-value of 0.36 (t=-3.96, df=47). This indicates that the two groups are still not significantly different.

A within-subject analysis was also conducted to determine if the groups significantly increased their spatial visualization skills. The paired t-test for the SketchTivity test returned a p-value of less than 0.001 (t= -4.81, df=32) and the Control group's paired t-test also returned a p-value of less than 0.001 (t = -3.96, df = 47), indicating that the spatial visualization skills of both groups were significantly increased.

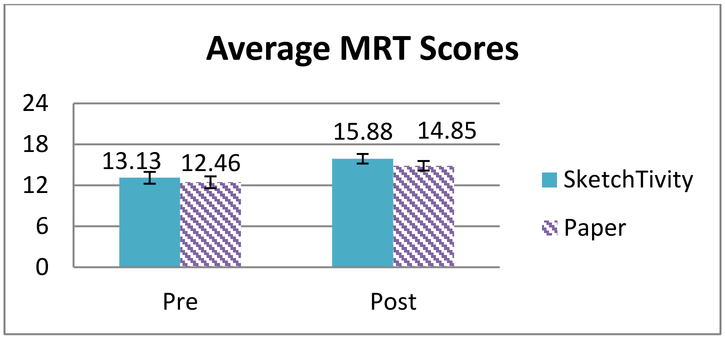

Figure 8. Pre- and Post-Course Average Mental Rotation Test Score for Each Group Shown with Standard Error Bars

5.2 Sketching Ability Results

Comparing the correlation between the two raters resulted in a Pearson correlation of 0.68 when treating the ratings like a continuous rating scale and a Cohen's Kappa of 0.62 when treating the data in a binary pass/fail. According to Cohen (1988), any Pearson correlation above 0.5 is considered a strong correlation in qualitative research, and any Cohen's Kappa between 0.61 and 0.8 is considered substantial. Therefore, the ratings given are reliable as both continuous data and binary data. The remainder of the data shown comes from a single rater.

Figure 9 shows the percentage of how each student's post-course sketch compared to the pre-course sketch among the three groups studied. Pearson's χ^2 test (Pearson, 1900) is used to compare the success rates through between-subject analysis of the SketchTivit

y and Control groups as well as the SketchTivity and Traditional groups. The χ^2 test between the SketchTivity and Paper groups returns a p-value of 0.10 (Z = 1.63, df = 41), indicating that the groups are not significantly different, but likely will be different with a larger sample size. The χ^2 test between the SketchTivity and Traditional groups returns a p-value of 0.477 (Z = 0.711, df = 41), indicating that the groups are not significantly different.

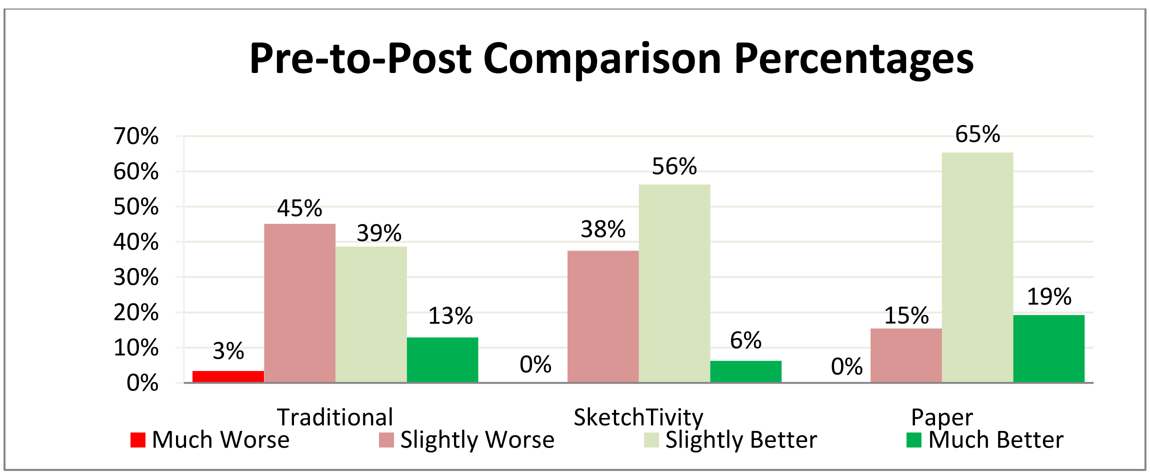

Figure 9. Frequency of Pre-to-post Sketching Ratings

6. Discussion

An analysis of the MRT results indicates that using SketchTivity improves students' spatial visualization skills the same as pen and paper sketching. As previous studies find sketching to be an effective way to develop visualization skills, finding sketching digitally to be as effective as analog sketching in this regard is a positive outcome as it shows that the SketchTivity program maintains the development of critical skills gained from analog sketching.

When observing the students' development of sketching abilities, the analyses show two important results. First, the trend of the percentage of students whose sketching ability improves indicates that SketchTivity is more effective at improving sketching ability than the Traditional method but less effective than the Perspective method with only analog sketching exercises. Second, neither the differences between the SketchTivity group and Traditional group nor the differences between the SketchTivity and Control group were found to be significantly different. These results indicate that while the early version of SketchTivity used by the students in this study was not as effective as analog sketching with more instructor feedback, results do indicate that teaching perspective sketching with SketchTivity may be more effective than teaching traditional engineering sketching.

Ultimately, our results indicate that using SketchTivity maintains improvements in key skills such as spatial visualization while improving students' sketching ability with less instructor feedback to students.

7. Future Work

The results indicate that SketchTivity helps to improve students' sketching ability, but a gap exists between the ability gained from students who use SketchTivity and those who only receive feedback from human instructors. This may be due to the increased scaffolding in the SketchTivity lessons (as seen in Figure 6), giving them less practice drawing on a blank surface. Future iterations of the system have included less scaffolding, which should aid in the development of the users' sketching ability. An example of a forthcoming improvement is the advanced cube exercise seen in Figure 10 which requires the user to draw construction lines before sketching a final cube. The system rejects construction lines not drawn in the proper location to aid users in developing their mental model of the cube. The user then draws a final cube based on the construction lines they drew. The developers also intend to provide more sophisticated forms of feedback like humanized dialogue. In this way, the system could become closer to a human instructor in effectiveness as well as be an excellent supplementary practice tool for learning design sketching.

There are also several features planned to be included in future versions of SketchTivity. More modules are in development including exercises in combining several primitives. This will allow students to improve their perspective abilities as they place multiple objects in the same perspective plane. Modules allowing users to sketch with less provided structure are also in development. These will give users more freedom to sketch in perspective but still receive feedback on how well they are maintaining the perspective planes. The inclusion of a user profile will allow users to track their progress over time using SketchTivity. This will help students to identify their own weaknesses to focus on as they perform more exercises. Lastly, a game-based approach is being explored through games like *ZenSketch* (Williford et al., 2017), a game designed to improve students' line drawing skills, in an effort to better motivate students to practice their sketching fundamentals and be more engaged with the system. Greater engagement generally results in more time spent and greater learning gains.

The authors are also interested in other aspects affected by learning to sketch in perspective from both instructors and SketchTivity. One skill of particular interest is how obtaining sketching skills affects students' creativity, willingness to draw free-body diagrams, and to use sketches to communicate design ideas. Future studies will attempt to understand this impact by measuring students' creative self-efficacy and idea generation ability.

8. Conclusion

Hand-drawn sketches are an important tool in engineering design. Sketches are used to communicate design intent and improve collaboration (Dym et al., 2005; Goldschmidt, 2007), and the practice of sketching improves abilities such as spatial visualization (Olkun, 2003). While previous work has shown that learning perspective-based sketching maintains these

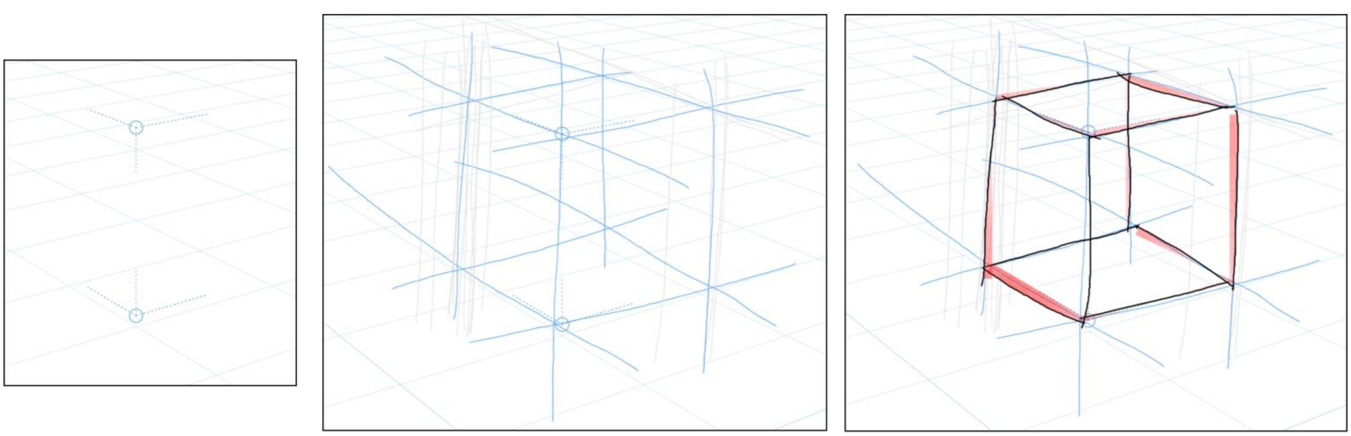

Figure 10. Advanced Cube Exercise with Reduced Scaffolding

benefits while improving sketching ability in engineering students (Hilton, Paige, et al., 2017), there are two major drawbacks to including it in engineering curricula. There is a lack of professors who can teach perspective sketching in engineering curricula, and the amount of time required to evaluate and provide feedback on student sketching assignments can be substantial. This paper shows that the implementation of an online intelligent tutoring system, SketchTivity, achieves the benefits of teaching perspective-based sketching with less instructor interaction.

The results of this study indicate that utilizing SketchTivity maintains the improvement of key skills such as spatial visualization while maintaining or improving the sketching ability of students when compared to students taught using a more traditional method of engineering drawing. However, the authors also observed that SketchTivity might not be as effective at improving sketching ability as teaching the perspective method with only human feedback. Therefore, SketchTivity will continue to be improved, and further analyses will be conducted to measure its future impact.

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