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Effectively Teaching Sketching in Engineering Curricula*

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Free-hand sketching is an essential skill for engineering communication and visualization. Sketching provides many benefits to engineers. This paper compares two approaches for teaching engineers to sketch. The traditional engineering approach was compared with an approach borrowed from industrial design, which emphasizes learning to sketch in perspective. The Perspective approach was expected to provide greater free-hand sketch ability and sketching confidence, but its impact on spatial visualization has not been explored. Pre- and post-course evaluations measured design self-efficacy and spatial visualization using the Revised Purdue Spatial Visualization Test and the Mental Rotation Test (MRT). Both sketching approaches improve MRT scores but had no differences between the groups. For initially low scoring students, similar trends are observed as when comparing the full sample size. The results show that the Perspective approach adds additional free-hand sketching skills while preserving the critical impacts on spatial visualization. Across the course, for both groups, design confidence and expected success both increased with reduced anxiety about doing design. The Perspective approach is as effective as the Traditional approach while also including additional skills in the same amount of course time.

Keywords: sketching; spatial visualization; visual communication; engineering curriculum

1. Introduction

The ability to generate visual representations is essential for engineering design [1–5], and as CAD programs have been developed, it has become easier to develop computer-generated renderings of a design. However, CAD has been found to hinder the design process if used too soon or too often, as it leads to fixation [2]. A better practice is to use hand-drawn sketches during the idea generation and development phase [6, 7]. Other benefits of sketching involve improved collaboration [8], improved conceptual understanding [9], and improved understanding of ill-defined problems [10]. How well a design is sketched can also influence how creative the design ideas are perceived [11]. Finally, sketching has been found to improve spatial visualization ability [12, 13]. Despite the many benefits of teaching free-hand sketching to engineers, it is not widely taught in the engineering curriculum [14]. This study presents two methods for teaching sketching in engineering and how the presented curricula can create more effective engineers.

Traditionally, sketching in the engineering curriculum is taught with the purpose of providing dimensions for a product to be created. This is accomplished through teaching drafting engineering drawings using simple isometric and sectional views [15]. As CAD has become more prevalent in Engineering Design courses, these types of sketches feed directly into CAD drawings. The inclusion of this type of sketching has been shown to improve skills such as spatial visualization, but otherwise, gives the students the same benefits as using CAD alone. The hypothesis of this paper is that the ability to generate more realistic sketches of objects can further improve spatial recognition while also improving sketching ability more than the traditional engineering approach. Courses in the Industrial Design curricula have developed pedagogy to train designers in sketching through the use of elements such as perspective view, shading, and ray tracing. According to The Engineer of 2020: Visions of Engineering in the New Century [16], the engineering profession must leverage innovative developments of non-engineering fields, and this still has not been accomplished. Therefore, in recent years, instructors in mechanical engineering have partnered with instructors from Industrial Design to develop a suitable curriculum to replace the sketching-based portion of a freshman-level engineering graphics course. This method of teaching perspective sketching has been introduced in engineering curricula to allow engineering students to benefit from the advances made in Industrial Design education.

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1.1 Traditional method

Introduction to Engineering Graphics and Visualization is a freshman-level cornerstone design course at the Georgia Institute of Technology in the Mechanical Engineering Department with the goal of teaching students to develop and interpret engineering drawings and representations. The first five weeks of the course are dedicated to drawing and the remaining 10 weeks are dedicated to solid modeling using CAD software. In the traditional version of this course, the sketching portion is primarily focused on developing engineering drawings such as those developed for manufacturing purposes. Two-dimensional and three-dimensional drawings are created, but three-dimensional drawings are only isometric. Almost all of the drawings are done using grid paper and straight-edge tools. Figure 1 shows an example shown in class on how to generate an isometric drawing of a complex shape. Note the use of a straight edge and graph paper. In general, the drawings in the class are intended to prepare the students to create computer-generated solid models in the latter portion of the course.

1.2 Perspective method

In recent years, professors in the Mechanical Engineering department at Georgia Tech have worked with professors from the Industrial Design department to implement the method of teaching sketching used in Industrial Design to the sketching portion of the Introduction to Engineering Graphics course in Mechanical Engineering. This method of the class includes teaching techniques such as thumb-nailing (Fig. 2a), perspective (Fig. 2b & c), primitives, drawing complex shapes in perspective, shading (Fig. 2b & c), and ray-tracing to create shadows that mimic a light source (Fig. 2c). Figure 2 shows a series of student work from assignments given throughout the first five weeks including (a) thumb-nailing a dorm room object, (b) drawing primitive basic shapes in perspective using shading to show surface texture, and (c) sketching a concept for a product. All of the assignments are presented during the lab session in a gallery style showcase where all of the students can walk around and see everyone's sketches and provided critiques and praise to their classmates. This method of the course focuses more on devel-

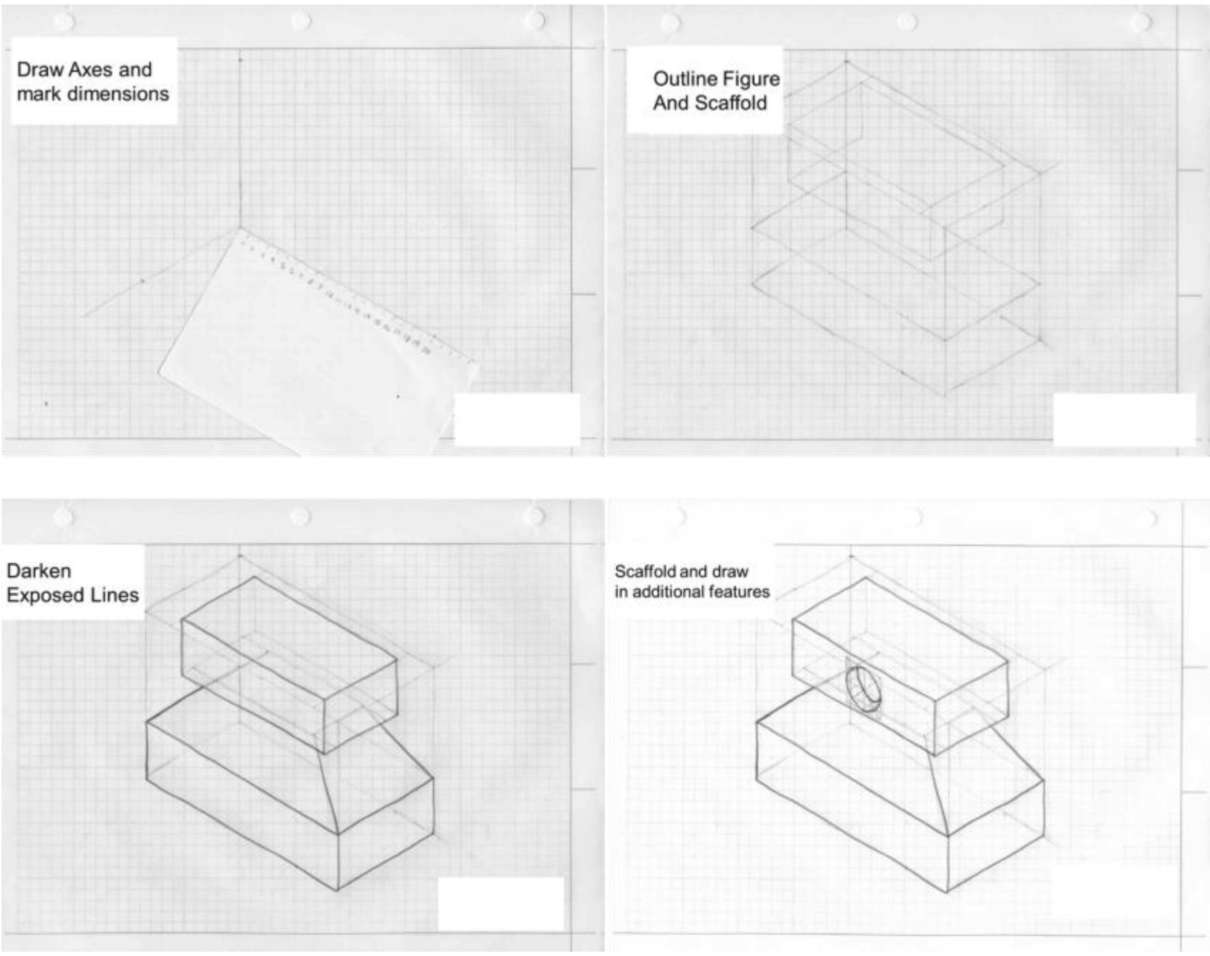

Fig. 1. Example from Traditional Class on how to draw in isometric view.

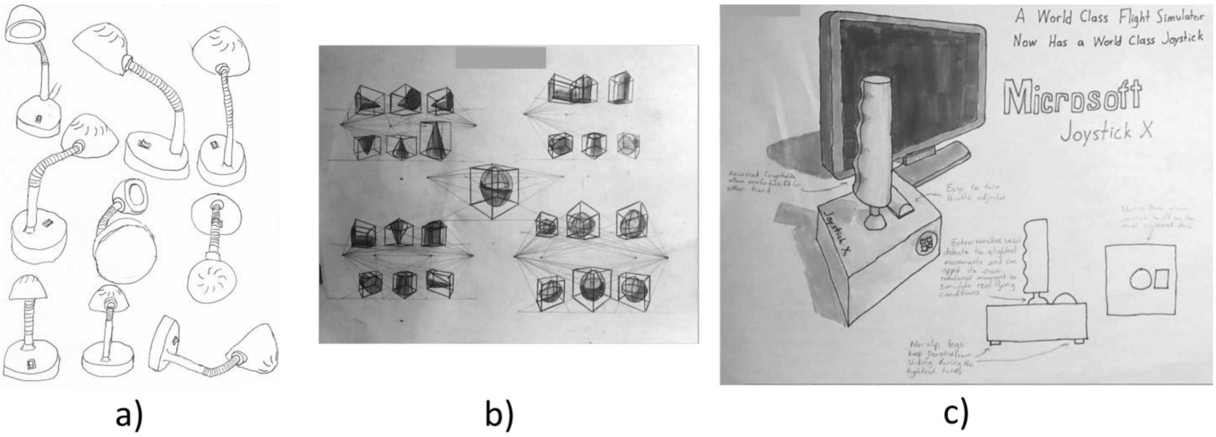

Fig. 2. Example of student work from Perspective method course: (a) thumbnails of a dorm room object, (b) exercise of multiple 3D shapes in perspective, (c) concept product sketching in perspective with appropriate shadows.

oping the ability to generate realistic renderings of objects and or ideas using sketching only.

2. Methodology

Both methods of teaching sketching are currently used in separate sections of the same freshman-level course in mechanical engineering. To study the impact of these methods, relevant skills were measured in students from both versions of the course over two semesters of the course. In total, 795 students participated in the study, with the vast majority being mechanical and aerospace engineering majors. The students completed pre-course and post-course evaluations using online survey distribution software to determine the impact of the course. The pre-course evaluation was given during lab session of the first week of class. The post-course evaluation was given during the lab session two weeks before the end of the semester. Students who did not complete both the pre- and post-course data collections were removed for analysis, leaving a sample size of 694. The evaluation included two scales testing spatial visualization skills and a design self-efficacy scale.

The two spatial visualization tests were the revised Purdue Spatial Visualization Test: Rotations (PSVT:R), consisting of 30 untimed questions, originally developed by Bodner and Guay (1997) [17] and revised by Yoon (2011) [18], and the Mental Rotation Test (MRT), consisting of 24 questions with a time limit of 12 minutes, developed by Vandenburg and Kuse (1978) [19] and revised by Peters (1995) [20]. Both tests present the participant with an object viewed from an initial angle and four images of similar objects viewed from various angles. The participant must then select the image that shows the object from the main image rotated in space. Each test was analyzed independently, and participant submissions for each test that did not complete the evaluation with sufficient effort (left more than half of the questions blank or gave the same answer choice for the majority of the questions) were also eliminated from the analysis. A three-question survey on effort was included following each test. No participants were eliminated based on the responses to these effort surveys alone. The eliminations resulted in a sample size of 657 (360 Perspective, 297 Traditional) for the PSVT:R, and a sample size of 675 (364 Perspective, 311 Traditional) for the MRT. The spatial visualization data for each test was analyzed between the two independent groups of students, Traditional and Perspective. As spatial visualization skills have been found to be crucial to success in engineering courses [5, 12], the spatial visualization data collected pre-course was also used to determine students who were initially low-scoring in this skill. Previous work by Sorby and Veurink (2010) found that students who scored below 20 significantly benefit from intervention [21]. Based on these findings for the PSVT:R, students who scored below a 20 were considered low-scoring, which resulted in low-scoring PSVT:R designations for 89 students from the Perspective group (24.7%) and 75 students from the Traditional group (25.2%). For the MRT, students who scored in the bottom 33% were considered low-scoring. The cutoff for these scores was found to be scores below 11 (of a possible 24) resulting in low-scoring designations for 118 students from the Perspective group and 103 students from the Traditional group. The low-scoring students from each group were compared.

The design self-efficacy survey, developed by Carberry, et al. (2010), [22], asked the students to rate themselves on their *confidence* in their ability to conduct engineering design, *motivation* to conduct engineering design, expectation of *success* when

Table 1. Sample Sizes of Data Groups

	Perspective	Traditional	Total
PSVT:R	360	297	657
Low-Score PSVT:R	89	75	164
MRT	364	311	675
Low-Score MRT	118	103	221
Self-Efficacy	184	159	343

conducting engineering design, and their *anxiety* when faced with the task of conducting engineering design. Unfortunately, we were unable to gather pre- and post-course data in design self-efficacy from the first semester, so only data from the second semester (n_{pers} = 184, n_{trad} = 159) was analyzed. Sample sizes of both the spatial visualization data and design self-efficacy data are summarized in Table 1.

3. Results

To determine if participants in the two groups began the study statistically equivalent in their spatial visualization skills, the pre-course surveys were compared, and the results analyzed using t-tests. The groups were compared again using the post-course surveys to determine if there was any significant change between the groups. Additionally, within-subject paired t-test analysis was run to determine if there was a significant change in the group.

3.1 Spatial visualization results

A t-test was run between the traditional and perspective groups' results of both the PSVT:R and MRT. A t-test verified that the groups began with comparible spatial visualization skills. The t-tests between the two groups for the pre-course PSVT:R returned a p-value of 0.73 (t = 0.345, df = 654), and the t-test for the pre-course MRT returned a p-value of 0.85 (t = 0.193, df = 673). The two groups started at similar levels.

Post-test scores were compared to determine if the two approaches had a different impact on spatial visualization skills. T-tests for post-course scores indicating no difference between the groups for the mean (PSVT:R p = 0.40, t = –0.844, df = 654; MRT p=0.69, t=0.402, df=673). The pre- to post-comparison for the PSVT:R can be seen in Fig. 3. All bar graphs indicate average scores for the sample and are shown with error bars indicating +/–1 standard error.

To determine if the course was improving scores, a paired t-test for the pre- and post-course was run. PSVT:R t-tests for both the Traditional group (p = 0.19, t = 1.32, df = 295) and the Perspective group (p = 0.280, t = –1.08, df = 359) indicates no improvements. On further investigation, a ceiling effect was observed as 29% of the participants missed 2 or less questions. The pre to post comparison for the MRT can be seen in Fig. 4. Paired t-tests were also run for both groups for the MRT and returned a p-value of <0.01 for both the Traditional (t = –13.9, df = 310) and Perspective (t = –14.9, df = 363) groups, indicating students are on average improving their MRT scores.

Since a ceiling effect was observed for the PSVT:R, and to further understand the impact of the course on students who began with low scores, the students determined to be low-scoring for each spatial visualization test were also compared. Comparing the PSVT:R means of the initially low-scoring students in the two groups' pre-scores returns a p-value of 0.96 (t = –0.054, df = 162), and comparing the post-course PSVT:R scores returns a p-value of 0.17 (t = 1.38, df = 162). These results indicate that the two groups were not statistically different at the beginning of the course or at the end of the course. Comparing the MRT means of the initially low-scoring students in

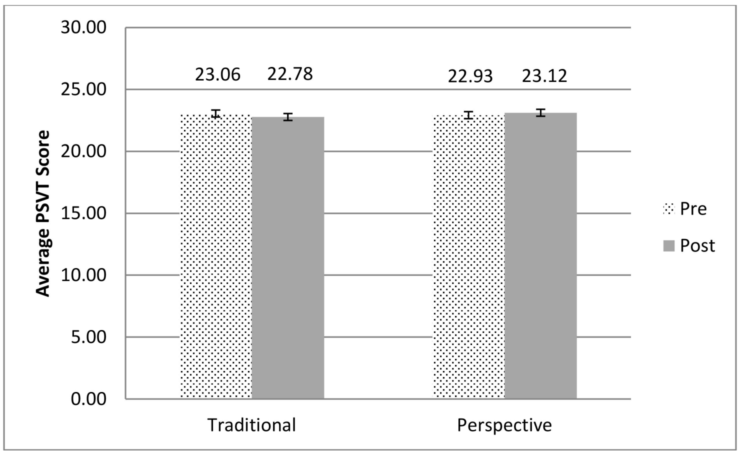

Fig. 3. PSVT pre- and post-course averages.

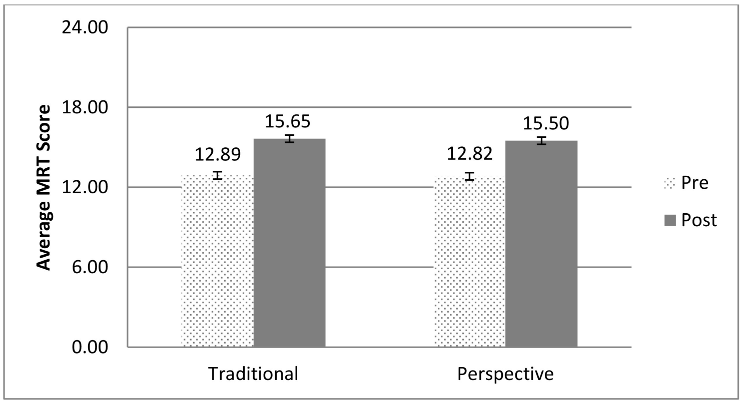

Fig. 4. MRT pre- and post-course averages.

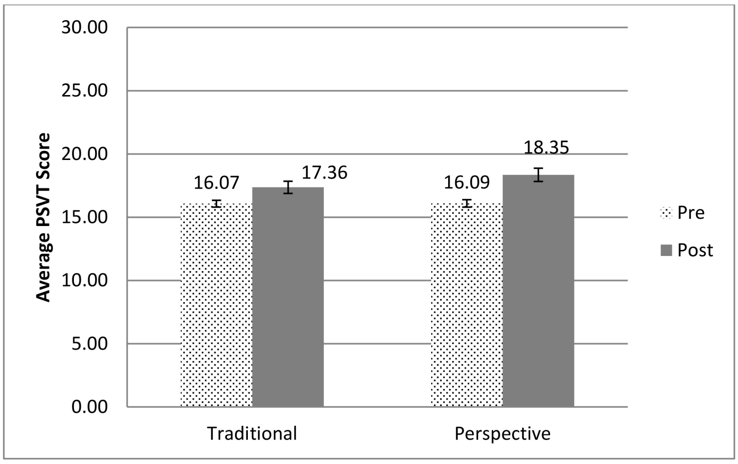

Fig. 5. PSVT:R pre-and-post scores of initially low-scoring participants

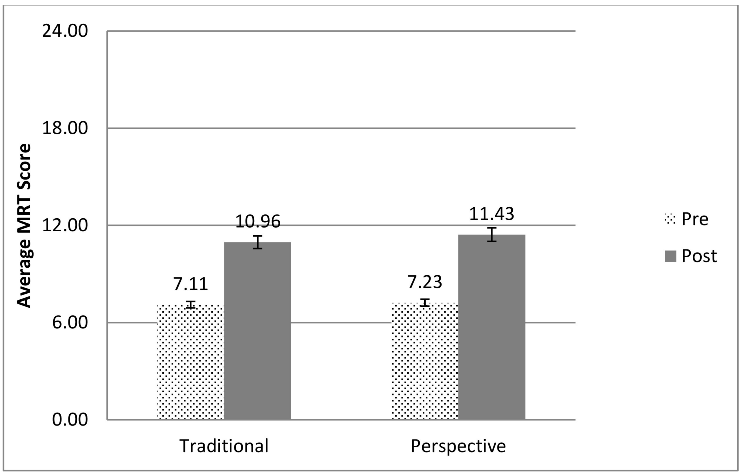

Fig. 6. MRT pre- and post-course averages for initially low-scoring participants.

the two groups' pre-scores returns a p-value of 0.68 (t = –0.408, df = 219), and comparing the post-course MRT scores returns a p-value of 0.41 (t = 1.38, df = 162). These results again indicate the two groups were not statistically different at the beginning of the course or at the end of the course. Figure 5 shows the pre to post comparison of the PSVT:R averages from the initially low scoring students. Paired t-tests were run to on each group returning a p-value of 0.01 (t = –2.66, df = 74) for the Traditional group and a p-value of <0.001 (t = –5.05, df = 88) for the Perspective group, indicating that both approaches are improving the students' PSVT:R scores. Figure 6 shows the pre- to post-

Table 2. Statistical Analysis Results- Design Self-Efficacy

	Between-subject Analyses (t-test)					
	Pre-course			**Post-course**		
	t	**p**	**df**	**t**	**p**	**df**
Confidence	0.732	0.23	341	1.25	0.211	341
Motivation	1.83	0.068	341	0.859	0.391	341
Success	0.790	0.43	341	0.514	0.608	341
Anxiety	–0.519	0.30	341	1.4	0.162	341
	Within-subject Analyses (paired t-test)					
	Traditional Pre to post			**Perspective Pre to post**		
	t	**p**	**df**	**t**	**p**	**df**
Confidence	–11.6	<0.001	158	–13.58	<0.001	183
Motivation	0.253	0.801	158	1.27	0.204	183
Success	–9.040	<0.001	158	–10.09	<0.001	183
Anxiety	3.646	<0.001	158	2.29	0.023	183

comparison for the MRT averages of initially low-scoring students from each group. Paired t-tests were run for each group and returned a p-value of <0.001 for both the Traditional (t = –13.9, df = 310) and Perspective (t = –14.9, df=363) groups, again indicating significant improvement..

3.2 *Design self-efficacy results*

The design self-efficacy scale from both groups was compared both pre- and post-course using a t-test. A within-subject paired t-test was also run for each group. The results of all of these analyses can be found in Table 2. The average pre- and post-course ratings of each group can be seen in Fig. 7 and Fig.8.

4. Discussion

The between-subject analyses of all the pre-course data suggest that the two groups are significantly similar at the start of the course, and the between-subject analyses of the post-course data suggest that the two groups remain significantly similar. Therefore, the Perspective method of teaching sketching can be said to be as effective as the Traditional method for developing the key ability of spatial visualization and impacting the students' design self-efficacy.

Also, the results of the within-subject analyses of the students suggest that both methods of teaching engineering graphics significantly increase students' spatial visualization. The exception is the results of the PSVT:R analyses, which show no significant change in ability. However, it can be argued that this lack of change is likely due to a ceiling effect as there is a significant increase when looking specifically at the students who were initially low-scoring. Finally, both methods can be seen to significantly increase the spatial visualization skills of students who begin with lower scores.

The within-subject analysis of the design self-efficacy survey suggests that both approaches to the course significantly increase students' confi-

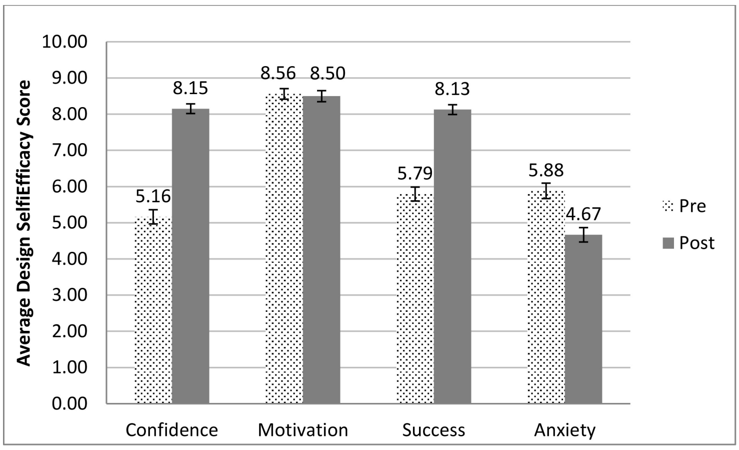

Fig. 7. Design Self-Efficacy Survey Responses—Traditional Group.

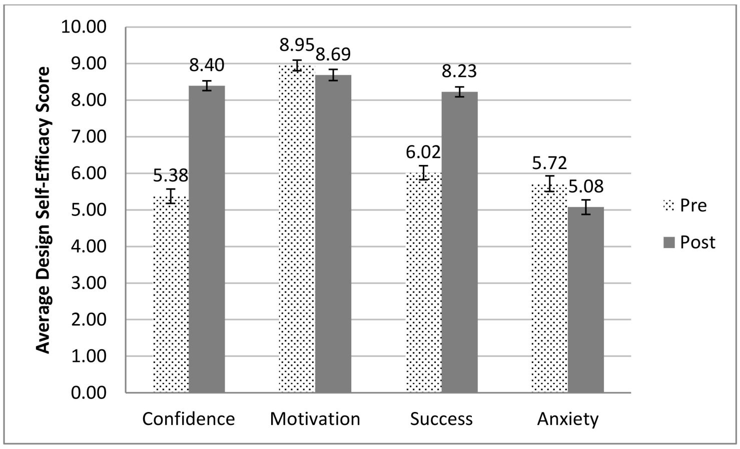

Fig. 8. Design Self-Efficacy Survey Responses—Perspective Group.

dence in being able to conduct engineering design, increase the student's perceived ability to succeed in engineering design, and significantly reduces anxiety associated with conducting engineering design.

All of these findings indicate that the Perspective method is just as effective as the more traditional method of teaching engineers how to draw at developing effective engineering designers while the Perspective method includes the development of a new skill of being able to draw realistic diagrams. Other studies on the same cohort of students have found the Perspective method of teaching the course to increase sketch quality at a significantly higher rate that the Traditional method [23]. This ultimately leads to the development of more well-rounded and capable engineering designers in the same timeframe as more commonly found curriculum. In conclusion, the results presented in this study support the notion that sketching continues to be an essential tool for engineering design, and continuing research is vital to ensuring the development of the most successful method of teaching sketching to engineers so that we may, in turn, continue to produce engineers with the tools needed to be successful.

5. Limitations

There are two major limitations of this study. The first was that the traditional method was only taught by one instructor and this instructor did not teach the perspective method in any of his sections. Due to this, any differences between the two groups could be attributed to the instructor and not the method. Future work should include one of the instructors teaching the alternative method to ensure the results are due solely to the method used. The second limitation is that both versions of the class follow the same curriculum for the CAD portion of the class. Therefore, the similar changes for each group in spatial visualization and design self-efficacy may be due to the similar portions of each method. Future work should observe changes in the students immediately after the sketching portion of the class to determine what changes are due to the sketching portion of the class and what changes are due to the CAD portion.

6. Future work

The main drawback of the Perspective method of teaching sketching is the lack of faculty with proper training to teach the course. For the current study, Mechanical Engineering faculty members were aided in developing the curriculum and gaining a greater understanding of the material by instructors from the Industrial Design department and faculty with dual appointments in Mechanical Engineering and Industrial Design. However, many universities do not have easy access to individuals with this expertise.

Other drawbacks include the additional time needed to evaluate student sketches and the desire to provide reliable evaluations of sketches and adequate feedback. Most evaluation methods of the detailed sketches produced in this method are primarily qualitative and require a trained eye to direct students on how to best improve. This is unfeasible for an ever-growing engineering student population.

In an effort to aid in the implementation of this method of teaching sketching in engineering education, an Artificial Intelligence Sketching Tutor is being developed in the form of an interactive pen-and-tablet-based online platform called Sketchtivity [24]. This AI system would help to supplement the shortcomings of the Perspective sketching curriculum by providing a series of progressive lessons based on the proven pedagogy used in Industrial Design. The system provides immediate feedback to students on their sketches by evaluating the data points of each sketch, determining its error, and showing the students the correct sketch. The program also allows students to see their progress in sketching skills in several parameters such as speed, accuracy, and steadiness. The implementation of such a system would allow an instructor with less experience in teaching perspective sketching to present core principles and allow the AI to provide the needed individual feedback to students. This would make it possible to teach a skill typically taught in a studio setting with smaller class sizes to lecture-style courses with larger class sizes.

As always, continuing research will be greatly needed to better understand the full impacts of differing methods of teaching sketching in engineering education. As the AI sketching tutor is developed and implemented into courses, observations of its impacts will be a crucial part of future studies. Preliminary studies have shown a satisfactory response from students using the system, but more work needs to be done in comparing the impacts of using the AI tutor versus a human instructor.

Another necessary element of future work will be to continue developing methods of evaluating sketches. The AI tutor will rely on having a consistent evaluation method in order to return human-like feedback to students. Preliminary work has been done to create a quiz and subsequent evaluation metric that could be implemented by an AI [25]. Also, having a more highly-developed evaluation metric will allow for more research to be conducted on the linkages between sketching ability and other design skills such as creativity and idea generation.

7. Conclusions

Sketching is an important, but sometimes overlooked skill for engineering designers. This paper presents two different methods for teaching freehand sketching in a freshman-level mechanical engineering course at the Georgia Institute of Technology. The first method teaches traditional engineering drawing that focus on teaching students to sketch 2D and isometric views of objects with the use of grid paper and straight edge tools. The second method teaches students more advanced sketching techniques typically found in Industrial Design courses including sketching in perspective and using ray-tracing to include shadows cast by the object. To evaluate the impact of this newer Perspective method has on skills that Traditional engineering sketching curricula have been shown to improve, the spatial visualization skills of two groups of students, one taught each method, were evaluated.

The results of the experiment suggest that the Perspective version of the course increased the spatial visual skills of students as well as the Traditional method. This finding shows that the Perspective method teaches engineering students new, more advanced, sketching skills without taking away from the other skills typically gained through more traditional engineering sketching curricula.

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Wayne K. Li is the James L. Oliver Professor, which is an endowed joint position between the Colleges of Design and Engineering at the Georgia Institute of Technology. Through classes and the Innovation and Design Collaboration (IDC), he leads joint teaching initiatives and advances interdisciplinary collaboration between mechanical engineering and industrial design. He teaches students that design behavior bridges the language and ideological gap between engineering and design.

Previously, Li led innovation and market expansion for Pottery Barn seasonal home products and was an influential teacher in Stanford University's design program where he taught visual communication and digital media techniques. He also led 'interface development' in Volkswagen of America's Electronics Research Laboratory and developed corporate brand and vehicle differentiation strategies at Ford Motor Company. Li received his Master of Science in Engineering (Product Design) from Stanford University, and undergraduate degrees in Fine Arts in Design and Mechanical Engineering from the University of Texas at Austin.

Tracy Hammond, PhD, is director of the Sketch Recognition Lab and Professor in the Department of Computer Science and Engineering at Texas A&M University, is an international leader in activity recognition (focusing on eye, body, and sketch motions), haptics, intelligent fabrics, smartphone development, and computer human interaction research. Dr. Hammond's publications on the subjects are widely cited and have well over a thousand citations, with Dr. Hammond having an h-index of 18, an h10-index of 26, and four papers with over 100 citations each. Her research has been funded by NSF, DARPA, Google, and many others, totaling over 3.6 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 M.S in Anthropology, an MS in Computer Science, a BA in Mathematics, and a BS in Applied Mathematics. Prior to joining the TAMU CSE faculty Dr. Hammond taught for five years at Columbia University and was a telecom analyst for four years at Goldman Sachs. Dr. Hammond is the 2011–2012 recipient of the Charles H. Barclay, Jr. '45 Faculty Fellow Award. The Barclay Award is given to professors and associate professors who have been nominated for their overall contributions to the Engineering Program through classroom instruction, scholarly activities, and professional service. Dr. Hammond has been featured on the Discovery Channel and other news sources.

Dr. Hammond is dedicated to diversity. She focuses a significant amount of her efforts on improving diversity in computer science and published an award winning paper at FIE on the topic. She regularly sends 5–10 students yearly to Tapia and Grace Hopper and has presented herself three times at Grace Hopper and Tapia, including mentoring workshops to junior faculty and undergraduates. She has recently founded a nonprofit organization, Wired Youth, with her graduate student Stephanie Valentine, teaching cybercitizen and computer science skills to young girls.

Julie S. Linsey, PhD is an Associate Professor in the George W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technological. Dr. Linsey received her PhD in Mechanical Engineering at The University of Texas. 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. Her research seeks to understand designers' cognitive processes with the goal of creating better tools and approaches to enhance engineering design. She has authored over 100 technical publications including twenty-three journal papers, five book chapters, and she holds two patents.