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A Scalable Online Platform for Evaluating and Training Visuospatial Skills of Engineering Students

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A scalable online platform for evaluating and training visuospatial skills of engineering students

University of Illinois at Urbana-Champaign

Introduction

Research in the last two decades has demonstrated the strong connection between visuospatial skills and engineering education (Barke & Engida, 2001; Board, 2010; Carter et al., 1987; Casey, 1992; Gimmestad, 1990; Lubinski,2010; Metz & Sorby, 2013; Newcombe, 2010; Priby & Bodner, 1987; Small & Morton, 1983; Sorby, 2009; 2011; Uttal and Cohen, 2012; Veurink, and Hamlin,2011; Veurink, & Sorby, 2012). Students who have good visuospatial skills are found to be better equipped to learn, reason, and solve complex engineering problems (Veurink, & Sorby, 2012). Recent attempts to introduce workshops and seminars for engineering freshmen students across the US has demonstrated success in improving their learning and increasing the retention rates (National Research Council, 2006; National Science Foundation, 2013), especially for students in minority groups such as female engineering students.

Because of their importance, researchers and instructors have put a lot of effort into evaluating and training engineering students' visuospatial skills (Maeda, & Yoon, 2011; Maeda, & Yoon, 2013; Sorby, 2009). However, previous methods often rely on traditional paper-based questions and face-to-face visuospatial training workshops, which are costly and time-consuming, especially for large classes. Given the nationwide trend in the increasing number of university engineering students, we have designed and evaluated an online platform to provide a low-cost, scalable solution to effectively evaluate and train visuospatial skills (Loyalka, et al., 2014). In addition, the online platform can facilitate the analysis of behavioral and error patterns, which can lead to design of intelligent features that improve learning through the use of adaptive and individualized learning modules.

In the current phase of development, our online platform is designed to offer a comprehensive assessment of visuospatial skills using a set of well-tested multiple choice and free-hand sketching questions. The platform also includes a comprehensive set of exercises that help students acquire effective strategies to perform visuospatial problem-solving. The online platform has great potential to lower the cost of evaluation and training. First, the automatic grading feature can provide immediate feedback to the student, and the instructor can more easily manage multiple exercises to a wide range of students to make the training process more efficient. A more efficient evaluation process enables the early assessment of visuospatial skills, which facilitate the identification of students with potentially inadequate visuospatial skills (Yoon, 2008). Early intervention can then be introduced to train their visuospatial skills, such that they will not become a barrier for them to pursue their career in engineering. Moreover, early assessments can provide information to better customize the course flowcharts for students. For example, for students with weak visuospatial skills, they can be recommended to participate in workshops to improve their visuospatial skills before they take courses that demand heavily on these skills. Second, the online platform enables the possibility to create a large nationwide database that allows the comparison across classes, departments, and universities. The database also provides the opportunity to apply data analytic techniques to identify various patterns that are otherwise difficult to detect using traditional methods such as paper tests. Third, the data collection method can capture students' responses at a fine-grained level. Our online platform not only can evaluate students' performance but also record students' precise behavior while they are solving the problem. For example, when students are tackling the engineering sketching questions, our platform will record students' drawing step by step. Based on those data, we can reconstruct their problem-solving process to gain insight about their problem-solving strategy.

The platform is also capable of keeping track of students' response in each test and their performance to identify potential difficulties the student may encounter to provide individualized feedback. These features enable testing and training visuospatial skills at a large scale.

The Online Platform Design

The online platform is a website built upon the most well-developed programming languages and frameworks that maximize the compatibility for different user configurations. The front-end of the platform is written by JavaScript, Python, and HTML. The back-end of the online platform is a Structured Query Language (SQL) database which stores students' information, grades and activities. These programming tools were chosen to create a stable, secure, and scalable online platform.

The online platform has two major functions: An interface for answering multiple choice questions and a free-hand sketching tool for answering drawing problems. The interface for the multiple choice questions (Figure 1) allows the student to answer questions by clicking on the correct answers, and the system will time-stamped all user actions and automatically determine if the final answers submitted are correct. For example, the interface can capture the amount of time spent on each question and how the students change their answer before they make the final decision. Moreover, it can randomize the order of options for each student. The interface can also present the questions in different orders – e.g., questions can be presented in the order of their difficulty levels. The automatic grading feature will provide feedback to students not only on their own performance, but also on the general difficulty of the questions based on general statistics derived from the larger population of students. This large database of user interaction data enables data analytics techniques to be applied to discover error patterns or other behavioral patterns to better understand or characterize learning difficulty encountered by individual

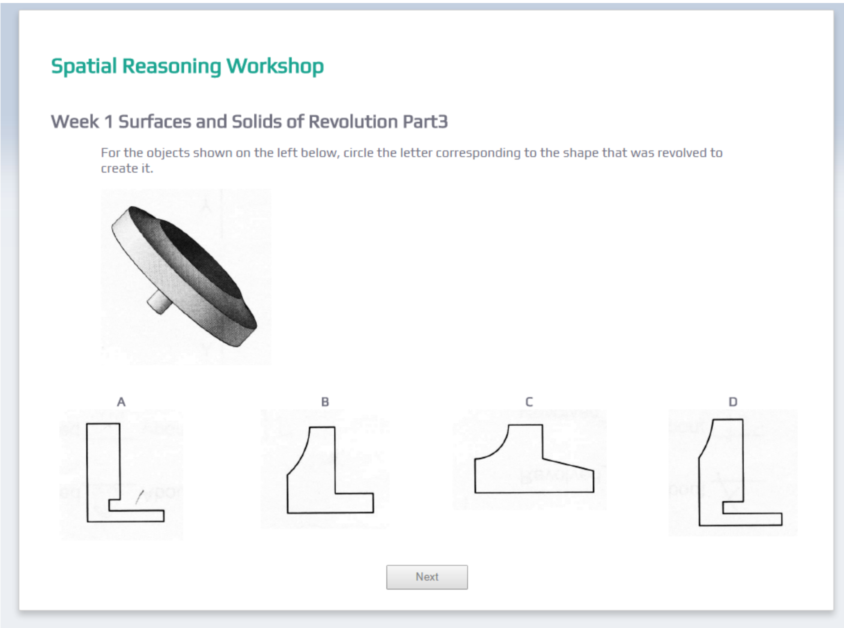

Figure 1. The multiple-choice interface of the online platform.

The free-hand sketching tool allows students to make isometric and multi-view drawings (which are the cores of training visuospatial skills) using their computer mice or other tracking devices (e.g., digital drawing pens). The free-hand sketching tool provides a working area with an isometric dot grid (Figure 2) or a dot grid to guide drawing (Figure 3). Students can add or delete a line between two dots without any constraints. After the drawing, the tool will take a screenshot of the current working area for grading purposes. The tool also keeps track of students' drawing process step by step. A comprehensive time-stamped log file documenting

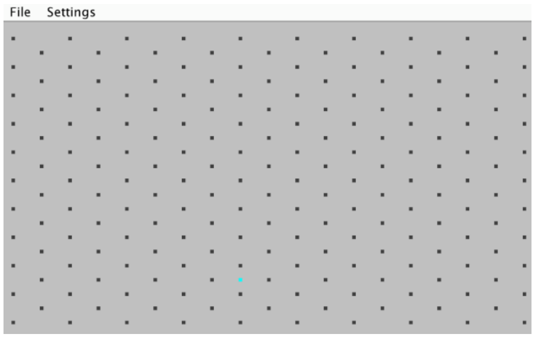

Figure 2. The free-hand sketching tool with the isometric grid.

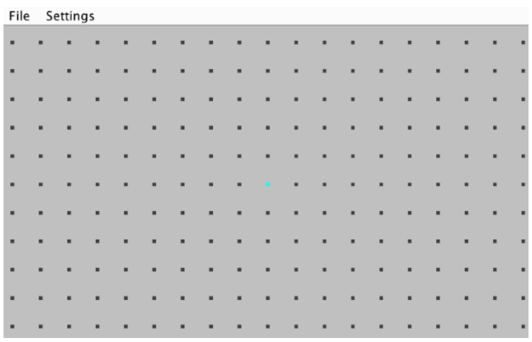

Figure 3. The free-hand sketching tool with the dot grid.

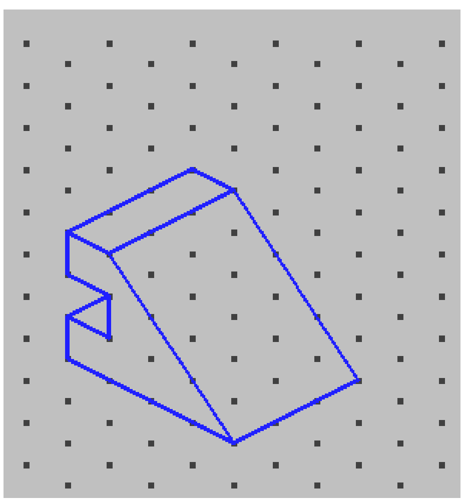

Figure 4. The student's generated answer.

students' drawing actions will be generated as well for future error pattern analysis. The screenshots (Figure 4) and log file (Figure 5) can easily automate the grading process as well. By applying simple data matching techniques, the online platform can automatically identify a student's mistakes by comparing the student's answers to the correct answers (Figure 6).

```
GridISO empty 29 "-4, -1, -4, 1" "-4, 1, -3, 1" "-3, 1, -3, -1" "-3, -1, -4, -1" "-4,
-1, -1, -3" "-3, 1, -2, 1" "-2, 1, -1, 1" "-3, -1, -1, -2" "-1, -2, 0, -1" "0, -1, 0,
0" "-1, -3, 1, -2" "1, -2, 0, -1" "1, -2, 1, -1" "0, 0, 1, -1" "0, 0, 1, 0" "1, -1, 2,
0" "2, 0, 1, 0" "1, 0, 1, 1" "2, 0, 2, 1" "1, 1, 2, 1" "1, 1, 0, 1" "-2, 0, -2, 1" "-2,
0, -1, 0" "-1, 0, -1, 1" "-2, 0, -1, -1" "-1, -1, 0, 0" "0, 0, -1, 0" "-1, 1, 0, 1" "0,
0, 0, 1"
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##HistoryItem## Type: LineAdd, Line: (-4,1:-3,1), Time: 2016/12/05 12:16:46
##HistoryItem## Type: LineAdd, Line: (-3,1:-3,-1), Time: 2016/12/05 12:16:51
##HistoryItem## Type: LineAdd, Line: (-3,-1:-4,-1), Time: 2016/12/05 12:16:52
##HistoryItem## Type: LineAdd, Line: (-4,-1:-1,-3), Time: 2016/12/05 12:17:13
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```

Figure 5. Example step-by-step drawing log

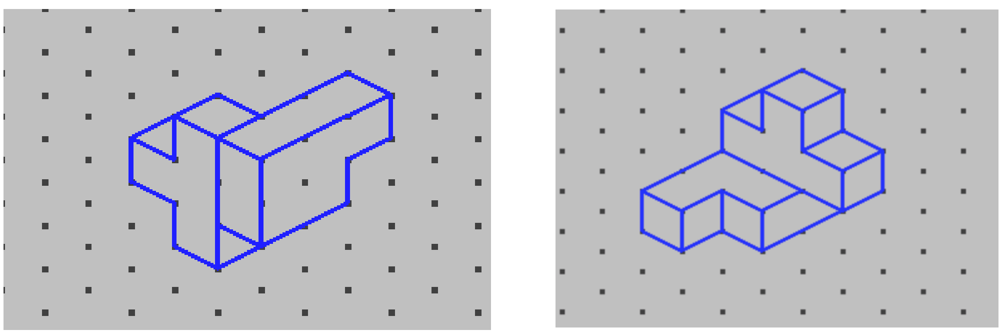

Figure 6. The student's generated answer (left) compares to the solution (right).

The Current Study

Although previous research has demonstrated the crucial role of visuospatial skills in the success of the STEM field, to our knowledge, there is no existing tool that facilitate the testing and training of visuospatial skills on a large scale (Lubinski,2010; Veurink, and Hamlin,2011;Veurink, & Sorby, 2012). In this study, our goal is to understand how effectively students can use the platform outside of the regular class times to minimize time and financial costs, and to what extent we can acquire user's data to improve future platforms.

Method

Participants

We deployed our online platform to four engineering courses that are designed for freshmen and sophomores in University of Illinois at Urbana-Champaign. All courses focus on the various aspects of engineering drawings where the spatial reasoning skills are strongly emphasized. We chose those courses because instructors from those courses have observed from their previous experiences that student's visuospatial skill is the key to learning and solving the problems in their classes. In particular, students who lack good visuospatial skills usually experience more difficulties than others. Two of those courses are in Theoretical and Applied Mechanics (TAM), one is in Aerospace Engineering (AE), and another one is in General Engineering (GE). Both AE and GE courses have similar goals: (1) to gain familiarity with the standards and conventions of engineering design graphics, (2) to gain exposure to computer aided design techniques, and (3) to develop sketching skills using different tools. The two TAM courses are about statics which also emphasize students' ability to understand the spatial relationship between objects. Through those courses, students will acquire a solid foundation for their future career in different engineering majors, such as Aerospace engineering, civil engineering, mechanical engineering and biological engineering. There were a total of 624 students from these four courses, who used our online platform to take the pre-course test to evaluate their visuospatial skills. We selected a subset of 30 students in the Aerospace Engineering course and the General Engineering courses to join our 7-week long workshop.

Procedure

Pre-course Test and Workshop Participants Recruitment. The pre-course test is a standard version of Purdue Spatial Visualization Test-Visualization of Rotations (PSVT: R), a widely used assessment in evaluating the visuospatial skills. A total of 624 students from two Theoretical and Applied Mechanics course ($N = 345$), one Aerospace Engineering ($N = 78$) course, and one General Engineering ($N = 201$) course took the PSVT: R test through the online platform at the beginning of the semester. The average of the pre-course test is 22.6 ($SD=5.18$) with similar distribution ($M= 22.92$, $SD= 5.11$) Maeda and Yoon (2001) found in a large scale assessment. Then, we sent out invitations via email to all students in the Aerospace and General Engineering course. 67 students responded our email and expressed their interest to participant. Due to the limited resources, we only plan to test our workshop with around 30 students. Since our goal is to help student with lower visuospatial skill, we chose students with relatively lower score in the pre-course PSVT:R test. In the end, we selected 30 of them with an average PSVT:R score of 21.3 ($SD= 5.31$) to join our online workshop. By the end of the semester, total of 17 students completed our online workshop. Participants who completed the workshop received $50 cash as compensation.

Online Visuospatial Skill Workshop. The online workshop was adapted and modified from an existing visuospatial workshop in our university and contains a series of exercises spanning seven diverse related topics (Sorby, 2011). Those topics included 1) Surfaces and Solids of Revolution, 2) Combining Solid Objects, 3) Isometric Drawings & Coded Plans, 4) Orthographic Drawings, 5) Flat Patterns,6) Inclined and Curved Surfaces, and 7) Object Reflections and Symmetry & Rotation of Objects About a Single Axis or Multiple Axes. All of those seven topics was covered or partially covered in the Aerospace and General Engineering courses as well.

Seven topics were scheduled from week 1 to week 7. In each week, participants were assigned a set of questions on the given topic through our online platform. The participant could take the assignment anytime anywhere. The exercise was either in the form of multiple-choice questions or a combination of multiple-choice questions and free-sketching problems. Before each exercise, there was an instruction page providing a sample question to help the students understand the question and practice using the platform to answer the questions.

Normally, the participant would spend 30-40 mins for each week. The assignment was released on the first day of the week and closed on the last day of the week. If the participant failed to complete the exercise before the deadline without proper excuse, the participant would be considered withdrawn and would be notified. By the end of the workshop, a total of 17 participants completed all assignments.

Individual interviews about the workshop were conducted with those 17 participants at the end of the workshop. All participants were asked about their experiences with the online platform and the workshop in general, such as their user experiences, strategies used in solving the problems, and suggestions for future platforms.

Post-course Test and Course Grade Collection. By the end of the semester, all students (N= 246) from Aerospace Engineering course and General Engineering course were asked to take the second round of PSVT:R test as the post-course test through the online platform including those 17 students who participated in the workshop.

Measures

Pre-course Test Score and Post-course Test Score. Both tests were the standard PSVT:R test with 30 multiple choice questions. Both tests have a maximum score of 30. Pre-course Test Score measured the visuospatial skills of students before taking the class and the workshop. Meanwhile, the post-course test score was the outcome variable which reflects student's visuospatial skills after the course training and the online platform workshop training. Since some students dropped the class after they took the pre-test, we only kept students with both pre-course Test and Post-course Test in the final dataset. This yielded a sample of 204 students.

Time Spent on the Online Platform. We used participants' timestamps when they are using the online platform to complete each week's exercise to calculate the time they spent each week.

Result

The focus of our analysis was to show whether our online platform can effectively train visuospatial skills with low cost; and if so, whether the training effect would be more pronounced for students who initially had lower PSVTR scores.

The Effectiveness of the Online Platform

To test whether students' visuospatial skill changed before and after our online workshop, we compared students' pre- and post- course PSVT:R test scores. For students who completed (N=17) our online workshop, the average post-course PSVT:R score (M = 24.94, SD = 3.38) was higher than the average pre-course PSVT:R score (M =22.65, SD =5.18). The paired sample t-test shows that the difference is significant; t = - 2.35, p = .03. The result indicates that students who took the online workshop significantly improved their PSVT:R test scores.

However, there are two potential issues which may weaken our interpretation of results. One is that the improved PSVT:R test may be due to taking the course instead of taking our online workshop. To test this possibility, we compared the improvement on pre- and post- course tests between students who took our online workshop and the rest of the students in the two courses. The result shows that the average improvement of students who took our online workshop (M = 2.29, SD = 4.01) was higher than the average improvement of the rest of the students in the class (M = -0.27, SD = 5.80). The Welch Two Sample t-test shows that the group difference was significant. This indicates that the online workshop seems to be more helpful for students to improve their PSVT:R test score; t = 2.418, p = .02. The second one was that students' initial visuospatial skills may differ between students in our online workshop and the rest of the students in the class, given that the student voluntarily joined the online workshop. By comparing the initial PSVT:R test score, we did not find any significant difference between two groups (M_worshop = 22.6, M_class = 20.9; t = 1.06, p = .30). Therefore, we did not see strong support for these potential alternative explanations, suggesting that our online workshop did seem to have a positive effect on students' visuospatial skills.

The Effectiveness of the Workshop for Students with Lower Initial PSVT:R Score

To test whether the training effect was more pronounced for students who initially had a lower PSVT:R score, we split students in our online workshop into two groups based on their pre-test PSVT:R score. Students who had scores higher or equal to the sample mean (PSVT:R score = 22.6) were in high-score group (N=11). Otherwise, students were assigned to the low-score group (N=6). The result shows that the average improvement of students in the low-score group (M = 5.17, SD = 2.72) was higher than the average improvement of students in high-score group (M =0.73, SD = 4.62). The Welch Two Sample t-test shows that the group difference is marginally significant; t = -2.17, p = .08.

The Time Spent on the Online Platform

After analyzing participant's timestamp extracted from the database. The average time participants spent on our platform for each week is 38.3 min (SD= 10.6 min). 80% participants took the exercise either after 6 pm on weekday or during the weekend.

Discussion

Previous research has demonstrated that a good set of visuospatial skills are crucial to future success in the STEM field (Lubinski, 2010; Veurink, and Hamlin,2011;Veurink, & Sorby, 2012). In this paper, our pre-course visuospatial skills assessment of 624 students shows that our online platform can efficiently evaluate the visuospatial skills of the engineering students on a large scale. The result of this paper also supports our hypothesis that students can improve their visuospatial skills through our online platform with low cost. By comparing student's visuospatial skill assessment in the pre-course and post-course tests, we found that students who used our online platform to develop their visuospatial skills significantly improved by the end of the semester. Also, students who took our online workshop received a significantly higher improvement than students who only took the class with the control of their initial visuospatial skills at the beginning of the semester. Meanwhile, students on average only spent 38 min on the workshop each week. Most of them took the workshop at home in the evening and during the weekend, which saved a lot of valuable traditional class time. During the individual interviews, 88% of students mentioned that one advantage of the online platform was time flexibility. In comparison to having regular meetings, taking the workshop anytime online could mitigate potential problems in conflict of busy schedules. Also, taking the workshop online saved instructors time and money to host the workshop regularly for a large group of students.

Furthermore, the improvement of students' visuospatial skill shows that our online platform can effectively and efficiently train visuospatial skills in a large scale.

The result also shows that students who initially had lower PSVT: R score tended to have more improvement in their visuospatial skills. When we interviewed one student who initially had a lower PSVT: R score about why she joined our workshop, she said *"……. When I saw my first assessment (pre-course test) score, I realized my visuospatial skill is not good enough and this workshop is the only way for me to catch up with other students in the class. …."* So, one potential explanation is that students who have lower PSVT: R score initially have stronger motivation to join and engage in our online workshop. Because of the improvement difference, identifying students with lower visuospatial skills seems important. Our online platform seems to provide a low-cost, scalable solution to deploy early assessments to identify students with lower visuospatial skills and to provide them early intervention.

Limitations

Although our pilot study shows that the online platform has the potential to more efficiently and effectively conduct testing and training of visuospatial skills in a large scale, it does have a few limitations. First, the number of students who took our workshop is small. Due to limited resources, we only recruited 30 students to use our online platform. The limited sample size constrained our ability to further explore all features of our online platform, which has the potential to perform error pattern detection, individualized feedback and instructions, and stroke-by-stroke analysis of sketching behavior. In the future, we plan to deploy our online workshop to a larger group of students to build up a large database, such that more complex analyses can be performed to bring more insight into the visuospatial skills learning process.

Second, the retention rate of our online workshop was not high. 13 out of 30 students dropped out in the middle. From our interviews, we learned that one reason could be that the materials provided by the online platform lacked novelty, as exercises were very similar but less advanced comparing to the materials taught in the class. More work is needed to fully understand why students dropped out and how to improve the retention rate for our future studies.

Third, students who stayed in our workshop could be more motivated than others in the course who either dropped out from our workshop or did not accept our workshop invitation. Motivated students are more engaged in the learning materials in general. Their improvement in the post-course test could be due to their higher motivation. In the next round of studies, we plan to measure their motivation level to understand differences in motivation could confound the learning effects of the training workshop.

Fourth, the materials we used in the online workshop were adapted from an existing spatial visualization workshop at our university. Both workshops are based on Sorby's Developing Spatial Thinking (2011), which has been demonstrated to be effective in training visuospatial skills. In previous visualization workshops, the goal was to understand the difference in spatial ability and spatial skills, to recognize the importance of 3d spatial skills for success in engineering, to improve 3d spatial visualization skills, and to provide an opportunity to practice the visuospatial skills through software and hand sketching. Students were required to attend the workshop once a week for an hour and complete the homework each week. Due to the nature of the online workshop, we only provided students instructions of the problem-solving strategy and ask them to complete an exercise each week with the same coverage of materials used in previous workshops. In this study, we did not have enough data to compare the effectiveness between workshops conducted using the current online platform and those that used traditional methods (e.g. lecture, paper-based exercise). On the other hand, compared to the traditional workshops, the training provided by our online platform does not require students to attend any regular meeting, which at least indicates that the online platform can more easily scale up to a larger number of students.

Future Directions and Plans

There are some features that we plan to implement in the next online platform based on the feedback and data we gathered from students and instructors in this pilot study. First, we plan to extend the auto-grading function from the multiple-choice questions to the free-hand sketching problems. In this study, all free-hand drawings were graded by human graders. During the grading process, we learned how course graders grade student drawings in daily instruction. We think that by applying simple data matching technique, it is feasible to fully automate the grading process. In this case, our fully automated platform can be applied at a much larger scale. Second, during the individual interview, students explained the strategies they used to tackle the problem and why they made certain mistakes. Based on this feedback and detailed step-by-step drawing data, we can provide individualized hints when students make mistakes and guide them to adapt a better problem solving strategy. Third, based on student grades and some behavior measures, it is also possible to personalize the training materials in terms of the difficulty, length and type of questions.

The online platform can facilitate the daily instructions as well. According to the instructors from the Aerospace engineering and the General engineering, when grading the sketching problems, the two major issues encountered are the times it takes for grading and the inconsistencies across graders. The automated grading feature of our future online platform can provide immediate and consistent feedback to students in real time. In addition, our online platform can keep track of students' performance in our workshop throughout the semester. When it is detected that the student encounters difficulties in certain topics, our platform can identify these topics and provide individualized feedback to the student, as well as to his or her instructor. The instructor can subsequently provide personalized course materials accordingly to help the students. In fact, our platform is ready to be deployed to integrate the online workshop with course materials, and thus, it can be used as a teaching tool. The platform can monitor student assignments and exam grades, and based on these performance measures, the platform can generate different exercises to optimize the learning process for individual students. We plan to work with the instructors in our next study to include the platform as a teaching tool.

We also plan to deploy the online platform to all incoming engineering students. Students will be assessed their visuospatial skills through our platform before class registration. Based on the assessment, their advisors will customize the student's course flowchart to make sure that students can acquire sufficient visuospatial skills before getting into courses that heavily rely on these skills. Also, before arriving on campus, incoming students with insufficient visuospatial skills can take the online visuospatial workshop to better prepare them before the semester begins.

Conclusion

In this study, a scalable online platform for evaluating and training visuospatial skills of engineering students was developed and tested in four large engineering classes, in which visuospatial skills are crucial. A subset of students from these courses participated in a 7-week-long online workshop using our platform. An evaluation of the visuospatial skills at the beginning of the semester showed that there was no significant difference in the visuospatial skills between students who took our online workshop and the rest of the students in these two classes. However, the comparison of the visuospatial skills by the end of the semester between those two groups indicated that our online platform could effectively help students improve their visuospatial skills. Moreover, this study also found that training through the online platform was more effective for students who have lower visuospatial skills initially. Both the individual interview and the behavior data suggests that our online workshop is a low-cost, scalable solution to large engineering classes. We also believe that many new features, such as error pattern analysis, fully automatic grading, and individualized instruction, can be incorporated in the future scalable online platform to further improve the usefulness of the platform for large engineering classes.

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