Sketching, Assessment, and Persistence in Spatial Visualization Training On a Touchscreen

Prof. Nathan Delson, University of California, San Diego

Nathan Delson's interests include mechatronics, biomedical devices, human-machine interfaces, and engineering education. He isCo-founder and Past President of Coactive Drive Corp., which develops novel actuators and control methods for use in force feedback human interfaces. Medical device projects include an instrumented mannequin and laryngoscope for expert skill acquisition and airway intubation training. He received his undergraduate degree in mechanical engineering from the University of California, San Diego, and then went on to get a doctorate in mechanical engineering from the Massachusetts Institute of Technology in 1994. He was a lecturer and Director of the Design Studio at Yale University for four years, and then returned to his alma matter, UC, San Diego, in 1999. He is now a tenured lecturer and Director of the Design Center in the Department of Mechanical and Aerospace Engineering. He teaches hands-on design courses, including an introductory design class, a mechatronics class, and a capstone design class. His interests in design education include increasing student motivation, teamwork, and integration of theory into design projects.

Dr. Lelli Van Den Einde, University of California, San Diego

Van Den Einde is a Teaching Professor in Structural Engineering at UC San Diego. She incorporates education innovations into courses (Peer Instruction, Project-based learning), prepares next generation faculty, advises student organizations, hears cases of academic misconduct, is responsible for ABET, and is committed to fostering a supportive environment for diverse students. Her research focuses on engagement strategies for large classrooms and developing K-16 curriculum in earthquake engineering and spatial visualization.

Sketching, Assessment, and Persistence in Spatial Visualization Training On a Touchscreen

Abstract

Spatial visualization training has been shown to increase GPAs and graduation rates in science, technology and math. Furthermore, prior research has correlated sketching on paper to improvement on the standardized spatial visualization test PSVT:R. However, to integrate additional content into an already full curriculum is challenging. To make spatial visualization easier to teach and more engaging to learn, an app was developed in which students draw orthographic and isometric assignments on a touchscreen. Each sketch is graded by an algorithm, and if the sketch is incorrect the students are provided with the option to try again or get personalized guidance from the app. This allows students to work independently and receive immediate feedback. In 2014, a trial using the App with college engineering students showed that it increased students' performance on the PSVT:R. The 2014 trial also showed that student persistence, as measured by the number of times they tried a sketch again without asking for help, correlated to increases in the PSVT:R. Since 2014, the App was modified significantly. The assignments were rewritten to take advantage of the touchscreen interface, and persistence was encouraged using gamification and by providing varying levels of guidance. Three trials were conducted with the updated app in college engineering courses; a 2016 a trial in an elective class (n=37), a 2017 trial in an elective class (n=32), and a 2017 trial in a required class where the app was assigned as homework (n=137). Overall the persistence metric increased from 40% in 2014 to 77% in spring 2017 (an increase of 93%). Larger gains occurred among students who entered the class with low PSVT:R scores (70% and below). These students are considered "at-risk" in terms of low graduation rates due to low spatial visualization ability. In 2014, 23% of these at-risk students improved to the point of moving out of the at-risk category. In 2017, this percentage increased to 82% and 67% (an improvement of 257% and 191%). This paper describes the modifications to the app and compares the 2014 trials to those conducted in 2016 and 2017.

Background

Spatial Visualization (SV) is the ability to mentally represent and manipulate 2D and 3D shapes. SV skills have been documented to be important in many STEM fields [1], and its importance is increasing with the use of graphics in medical imaging, computer visualization, and Computer Aided Design. A seminal study by Sorby [2] showed that SV skills are learnable, and a single course has been demonstrated to improvement SV skills. A summary of Sorby's work [3] covers the period from 1993 to 2012 with over 7,000 students; this study and shows how graduation rates in engineering have significantly increased due to SV training.

A key component of effective SV training is freehand sketching of isometric and orthographic shapes, and as stated by Sorby the "importance of sketching in developing 3-D spatial skills cannot be understated" [2]. In addition, sketching skills have benefits beyond SV, and has been correlated to communication, teamwork, and creativity [4]. Based on the value of SV training, the National Science Foundation funded a program in 2009 called "Engaging Students in Engineering" which endorsed adding SV training with sketching in STEM curriculum [5]. In addition, SV training has been highlighted as beneficial for increasing the number of women and other underrepresented minorities in STEM [6]. A workbook with sketching assignments has been developed specifically for SV training [7].

As SV training approaches have been developed, there became the need to assess its effectiveness. The Purdue Spatial Visualization Test: Rotations (PSVT:R) [8] is the most widely used metric, and improving students' PSVT:R scores has been tied to increased graduation rates [3]. Standard practices is to perform a PSVT:R at the beginning and end of a course. Assessment also considered whether SV training was elective or required. An elective class would attract students who are more motivated, and therefore can have a self-selection bias. Accordingly, when SV training is required then study results more clearly show the causal benefit of SV training. In the early years of the Michigan Tech study [3] SV training was elective, but in the later years of the study the SV course became required, and with self-selection bias removed SV training continued to show benefits.

Despite the benefits of SV training, relatively few engineering programs have made substantive changes to their curriculum to explicitly include SV training [9]. Engineering curricula are notoriously full, and for many programs finding space for a class on SV is difficult. In order to make SV training more efficient and easier to teach, the authors developed an app where students would sketch on a touchscreen, and an algorithm automatically grades the sketch. Automated grading allows students to work independently without impacting lecture time. In a 2015 study [10], the assignments used were from an SV training workbook [7]. In this study, when a student's sketch was incorrect they had the option of trying on their own again or peeking at the solution. The number of times a student would retry a problem on their own was used to quantify their persistence. A key finding of the study was that gains in PSVT:R scores can be bimodal and that students with higher a persistence metric had an average gain of 45%, while students with a low persistence metric actually had a slight drop in scores with an average of -4% change. This study showed that persistence was correlated with SV training gains, but it remained to be seen if persistence could be increased.

The use of touchscreen to teach sketching skills has also been done by Hilton et. al. [12]. The initial emphasis in this research was on training industrial design students where the aesthetics of the sketches was important, and feedback was provided in areas such as ability to draw straight lines and round circles [13]. The research question posed [12] was whether industrial design instruction would be beneficial to engineering students. A number of metrics where used to evaluate the training, yet the gains in PSVT:R pre and post tests was less than 1%. The trial by Hilton et. al. did show higher improvements in the Mental Rotation Test [15], yet this test is not the one correlated with increased graduation rates [3]. Accordingly, the type of sketching and feedback is an important factor in SV training, especially in regards to the PSVT:R metric which has been tied to increased graduation rates.

SV training has been shown to be beneficial and can increase graduation rates in engineering. However, for wider adoption to there is a need to make SV training easer to teach and not significantly reduce lecture time in other subjects. The use of touchscreens holds promise, yet the type of assignments and feedback to the students is critical. In addition, there can be a wide variation in student persistence, which has been shown to be a key factor in educational success in many areas [15]. Therefore, a challenge for eLearning tool for SV training is maintaining student engagement and persistence.

Introduction

In order to facilitate independent SV training, a software app, Spatial Vis™, was developed where students perform their sketches on a touchscreen [10], [11]. A key advantage of this approach is that students receive immediate feedback, which increases engagement. In addition, students can work independently. Since there is a wide range of SV skills among incoming students, some students will need more time to complete the assignments and the ability to work independently will allow these students to develop their skills without taking up class time.

In an early implementation of Spatial Vis™ [10] persistence was correlated to SV improvement. The aims of this study are to determine if persistence and effectiveness of the SV training can be increased. Improvements were made to the app in the following areas:

- Gamification to motive increased persistence.
- New assignments that take advantage of the digital interface.
- Data mining of prior student work to identify common areas of difficulty, and more gradually increase assignment difficulty in these areas.

Following these modifications to the SV App, three pilots were conducted. In winter 2016 and winter 2017 an *elective* 1-credit SV class. It was open to mechanical engineering and structural engineering students. Students were given three hours per week in class to do the App with teaching assistant support. In Spring 2017, the App was added to a *required* engineering graphics course for structural engineering students, and the App was assigned as homework. This paper provides a comparison between results from the 2014 pilot study and the three more recent pilot studies conducted after App modifications.

SV Training App Improvements

The improvements in the Spatial Vis™ app between 2014 and 2017 are described by Cowan et. al. [16]. The assignments used in 2014 [10] were temporarily licensed from the publisher of an SV workbook [7]. By 2017, all new assignments were generated and utilized features of the digital interface such as use of colors and constructions lines, that cannot be incorporated into a black and white paper book. The new assignments, gamification, and improvements to the app interface are described below.

The initial Spatial Vis™ application had several key user interface features such as the assignment window, sketching window, toolbar, and save button (see Figure 1). The assignment window describes the task students are to complete. The sketching window is where students draw their solution to the assignment. The sketching window and the assignment window each have a reference dot to prompt the student to know where in the sketching window they need to draw their solution for the grading algorithm to correctly score their submission. In the early versions of the app, the toolbar featured an eraser, pencil, and help button. When the user clicked on the save button in the top right corner, the grading algorithm was initiated. The grading algorithm produces a pop-up window that gives the student immediate feedback if their solution is correct or not. If the solution is correct, the student moves on to the next assignment. In the 2014 version of the App, if the solution was incorrect, the student could either retry the assignment or peek at the solution. If the student chose to peek at the solution, the sketching window would show which lines were correct or incorrect, and which lines were missing from their sketch for it to be graded as correct. The student would still need to correctly draw the solution to get credit for the assignment.

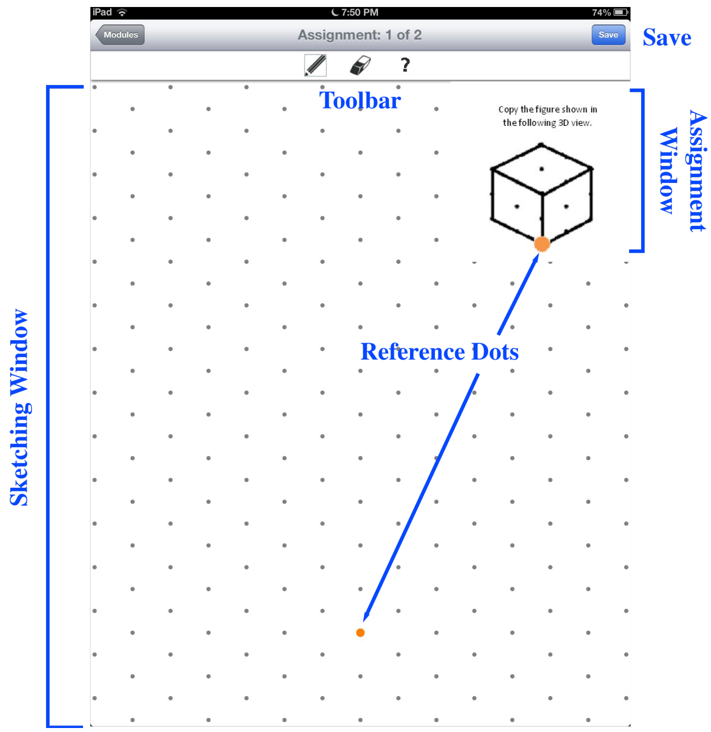

Figure 1: 2014 Assignment and Sketching Window

Based upon the findings of the 2014 study, the app was modified to increase student persistence. Digitized student data obtained from the 2016 trial was reviewed to determine which assignments required students to attempt multiple times in order to complete them. For these assignments, the difficulty was more gradually increased, sometimes separating new concepts into multiple assignments. Visual cues were added to early assignments to make them easier to complete as shown in Figure 2. There were 9 lessons in the app including: 2D Rotations, Isometrics, Orthographics, Sloped and Curved Shapes, Flat Patterns, Rigid Body Rotations, and Assembly.

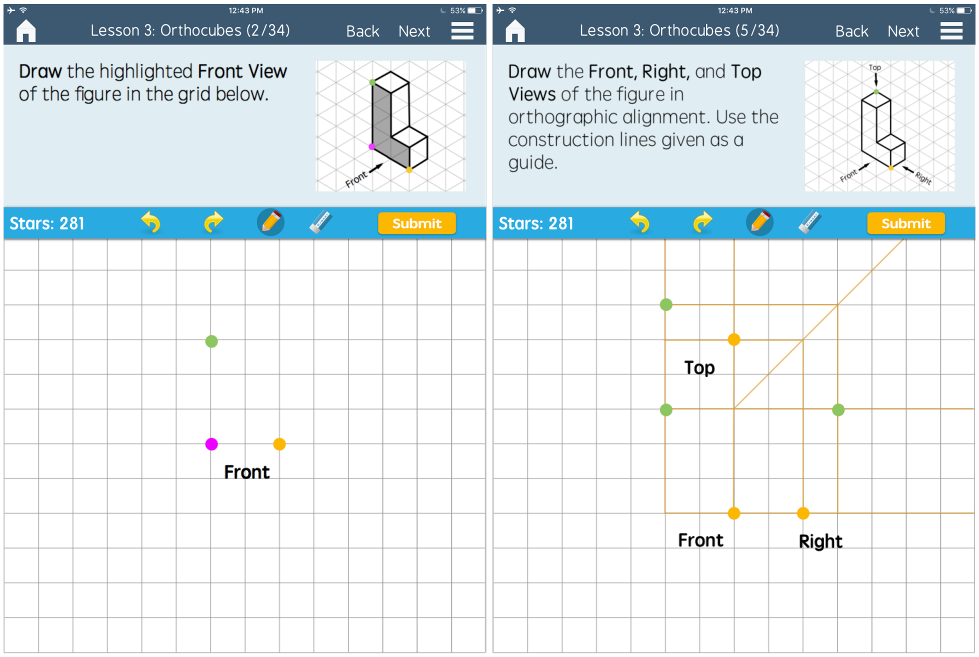

Figure 2: 2017 Assignments with Visual Cues

An intermediate level of help was also added (see Figure 3). In addition to the peek function that was available in 2014, a hint feature was added. The hint tells the user which parts of their drawing are correct by highlighting them in green and removing the incorrect lines. If a student uses a hint and most of their submission remains in the workspace then the student is close to the solution. Alternatively, if the student uses a hint and most of their submission disappears then they know they need to rethink the problem, ask for help, or possibly use a peek.

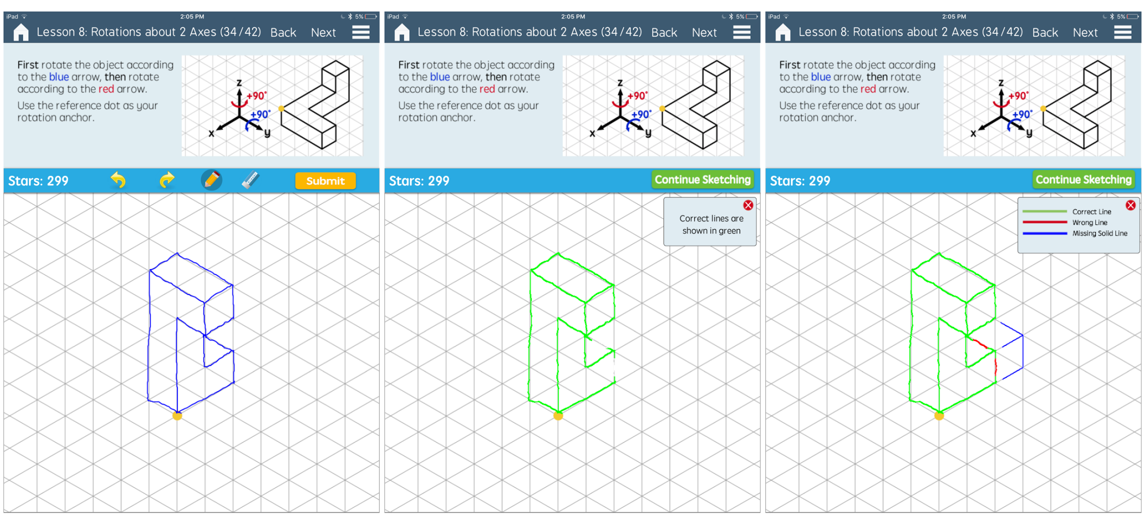

Figure 3: Original Submission with error (left), Hint Feedback (middle), and Peek Feedback (right)

In addition, gamification was added to the App to encourage persistence. Students now receive three stars for each assignment they solved correctly without any assistance regardless of how many times they attempt the sketch. If a hint is used, then they are awarded two stars for the problem and if a peek is used then students earn only one star when they successfully complete the sketch.

Finally, we incorporated test questions for the last three questions of each lesson. These assessments were chosen to be of moderate difficulty, and the hint and peek features are disabled. These test questions were incorporated to try to incentivize students to learn the material in each chapter rather than relying on the hint and peek features. Students were aware that they would have to eventually complete three assignments without help features before they could move on to the next chapter. Test assignments were incorporated in some of the 2014 lessons, but they were rewritten in 2017.

The Spatial Vis™ application runs on iPhone and iPads, as well as Android smartphones and tablets. However, all trials described in this paper were run with iPads.

Overview of Classroom Trials

This paper compares four classroom trials conducted at University of California at San Diego (UCSD). The first trial was implemented in 2014 [10] in MAE7, an elective class for aerospace, mechanical, and structural engineering students (n=52), before the recent app improvements were incorporated. In 2016, all assignments were completely rewritten, the hint and peek options were implemented, but not all assignment and app improvements were made. The winter 2016 trial (n=37) was conducted in the elective MAE7 class again. This year half of the students did all of their assignments during scheduled lab sessions with a tutor available for help, while the other half of the students had scheduled lab sessions every other week and did the off-week assignments as homework with checked out iPads. By 2017, all the app improvements described above were incorporated. The trial in winter 2017 was in the MAE7 elective class (n=32), and all student work was completed during scheduled lab sessions with a tutor available for help. In all MAE7 lab sections, students could leave the lab early when they finished their assignments for the week. In spring 2017 SV training was added to a required structural engineering course, SE3, (n=137) in which the assignments were done as homework using iPads checked out from a maker studio. The MAE7 trials were all elective and thus the results are subject to self-selection bias, but in the SE3 trial the SV training was required and thus there is no self-selection bias. Moreover, the in the SE3 trial the SV training did not reduce lab or lecture time of other subjects because the app was assigned as homework.

Methodology

To measure student's spatial visualization skills, following the work of Sorby and others [2] [18], we used the PSVT:R test. In each class, a pre- and post- spatial visualization test PSVT:R was administered with a test time of 20 minutes. Students who missed either a pre- or post-test were excluded from the study. This study was reviewed and approved to be in compliance with federal regulations regarding the protection of human subjects (IRB project number 130252SX).

Of specific interest are students who entered the course with low pretest scores. A key objective of SV training is to increase graduation rates in STEM, and the Sorby studies [3] showed that graduation rates within engineering were higher for those who scored above 70% on the PSVT:R pre-test, yet that those that participated in SV training could bring their graduation rates up substantially. These Sorby studies required SV training for students with pre-test scores below 60%, yet these same studies showed that this group leap-frogged students in graduation rates with pre-test scores between 60% and 70%. This implies that all students with pre-test scores below 70% would benefit from SV training. Other recent spatial visualization studies have also used the 70% threshold as an indicator for a need for SV training [18]. Accordingly, in this analysis the student's whose pre-test was ≤ 70% are categorized as "at risk" for low graduation rates due to low SV skills.

Within the "at risk" group, the average gains in PSVT:R scores does not tell the complete story, since the gains can be far from a normal distribution. In a prior study [10] students with a low pre-test scores (defined as ≤ 70%), there was a bimodal distribution in PSVT:R gains; one subgroup had significant average gains of 43% (σ=9.7%), while the other subgroup has minimal gains of -4% (σ=9.8%). The difference in these 2 groups was correlated to students' persistence, which was measured by how often a student retried an assignment before asking for a hint or peek. When the Spatial Vis app was improved to encourage persistence, the number of students with significant improvement almost doubled [16]. Accordingly, a key challenge in SV training is to engage students, and effectiveness of SV training can be characterized by the percentage of "at risk" students who have significant gains in PSVT:R scores.

A question remains as to what an appropriate threshold is to distinguish significant improvement among the "at risk" students. A prior study had characterized significant improvement as being above a 10% increase in PSVT:R [17]. However, this 10% threshold was criticized by a reviewer as arbitrary. We agree with this criticism, and a new criterion for defining significant improvement was developed. We sought a criterion that recognized the possible bimodal component of the data and also reflective of the correlation of PSVT:R scores to graduation rates. Accordingly, we chose as one metric for assessment of the effectiveness of the SV training to be the percentage of students who entered the course with a PSVT:R of 70% or lower, but then raised their PSVT:R to above this threshold. This metric captures gains in SV skills among students that need it the most, and the 70% threshold corresponds to the skill level that is correlated to higher graduation rates. This metric can be seen as an indicator of the percentage of students who moved from the "at risk" category for low graduation rates due to low SV skills, to outside of this category.

In addition to the pre- and post- PSVT:R tests, the app recorded data of each student's sketch attempt. A metric that reflects students' SV ability is how often a student's first sketch attempt is correct, which is indicated by the "Percent Correct First Try (nCFT)." Another SV ability metric is the average number of attempts, since higher ability students should be able to complete assignments in fewer attempts. A third SV ability metric is the average number of attempts in the test assignments at the end of each lesson, indicated by "Avg Num App Test Attempts." The persistence metric identified in the 2014 study is the Percent Tried Again Without Peeking normalized by the Number Wrong on the First Try. The normalization is necessary, since if a student gets an assignment correct the first time, then they do not have the opportunity to demonstrate persistence.

Results

The results are analyzed by separating the class into three groups based upon their pre-test scores, Low (<=70%), Mid (70%< x <90%), and High (>=90%). For comparison, the results of the earliest trials in the group from 2014 are shown in Table 1, and the latest trial in the group from spring 2017 is shown in Table 2.

Table 1. Overall Performance Results for Students of All Test Groups in the 2014 Trial in Elective Course MAE7.

	Pre Test Group: Low (n=13)	Pre Test Group: Mid (n=17)	Pre Test Group: High (n=22)	All Groups (n=52)
Avg. Pre-Test Score	53% σ=9.8%	78% σ=5.9%	93% σ=4.4%	78% σ=17.2%
Avg. Post-Test Score	61% σ=13.2%	87% σ=7.9%	90% σ=6.0%	82% σ=15.0%
Avg. Test Improvement	18% σ=25.8%	12% σ=11.9%	–2% σ=7.8%	7% σ=17.2%
Percent Correct First Try (nCFT)	35% σ=18.0%	59% σ=14.2%	74% σ=15.4%	59% σ=21.8%
Percent Tried Again Without Peeking (nARNHC/nWFT)	16% σ=16.6%	45% σ=28.5%	50% σ=30.5%	40% σ=30.1%
Avg Num App Test Attempts	2.3 σ=0.9	1.8 σ=0.7	1.5 σ=0.7	1.8 σ=0.8

The results in Tables 1 and 2 follow similar trends in terms of pre- and post- test data. Improvement is highest among the Low pre-test group (18% for the 2014 trial and 23.6% for the 2017 trial), which drops to 12% and 6% for the Mid group, and actually sees a slight drop of -2% & -1.5% for the High group. A minimal increase or drop in scores is to be expected among students who start the class with high scores, due to the multiple-choice nature of the PSVT:R test. The trends in SV ability metrics also follow as expected, with students with a high pre-test score having higher Percent Correct First Try and a lower Avg Num App Test Attempts.

Table 2. Overall Performance Results for Students of All Test Groups in the Spring 2017 Trial in Required Course SE3.

	Pre Test Group: Low (n=20)	Pre Test Group: Mid (n=44)	Pre Test Group: High (n=15)	All Groups (n=79)
Avg Pre-Test Score	55.8% σ=13.4%	79.6 % σ=7.2%	94.0% σ=3.8%	76.3% σ=15.8%
Avg Post-Test Score	74.2% σ=15.0%	86.1% σ=12.3%	93.3% σ=8.8%	84.5% σ=14.0%
Avg Pre-Post Test Improvement	23.6% σ=19.2%	6.0% σ=13.3%	-1.5% σ=9.9%	9.0% σ=16.9%
Percent Correct First Try (nCFT)	52.5% σ=10.5%	58.1% σ=12.1%	71.1% σ=10.2%	59.2% σ=12.9%
Percent Tried Again Without Peeking (nARNHC/nWFT)	57.7% σ=27.0%	79.5% σ=19.2%	94.7% σ=8.5%	76.8% σ=23.5%
Avg Num Attempts	2.56 σ=.77	2.33 σ=.92	1.67 σ=.40	2.26 σ=.86
Avg Num App Test Attempts	2.95 σ=1.0	2.75 σ=1.4	2.06 σ=1.1	2.67 σ=1.26

Differences between the 2014 and 2017 trials are apparent. The overall app improvement increased from 7% to 9% (a 28% improvement). An even larger improvement is seen in the pre-test low group which increased from 18% to 23.6% (a 31% improvement). The differences in Avg Num App Test Attempts is not directly comparable since the test questions themselves were changed.

The persistence metric, Percent Tried Again Without Peeking (nARNHC/nWFT), saw a significant increase. For all groups in the class persistence metric increased from 40% in 2014 (Table 1 column 5) to 77% in 2017 (Table 2 column 5), which is a 93% increase. There was an even larger increase for the Low group; in 2014 the persistence metric for the Low group was 16% (Table 1 column 2), and it increased in 2017 to 57.7% (Table 2 column 2), which is a 261% increase. The Mid and High groups also saw a significant increase.

The effectiveness of the SV training in shown in Table 3 in terms of the number of students who enter with SV scores that put them in the "at risk" category (<=70%) and complete the course with SV scores above that category. These results are shown for the four trials.

Table 3: Low Pre-Test Students (PSVT:R <= 70%)

Year	Average Pre-Test Score	Average Post-Test Score	Students that moved out of Low Pre-Test Group (Post-Test above 70%)
MAE7 2014 (n=13) *elective*	55%	64%	23%
MAE7 2016 (n=10) *elective*	53%	61%	40%
MAE7 2017 (n=11) *elective*	61%	80%	82%
SE3 2017 (n=27) *required*	57%	75%	67%

As seen in Table 3, there was a significant increase in SV training effectiveness among students entering with low PSVT:R pre-test scores. In the MAE7 elective class, in 2014 there was an average gain of 9% (55% increased to 64%), while in 2017 there was an average gain of 19% (61% increased to 80%). In terms of impact on "at risk" students, the percentage of students who moved out of the low pre-test group increased from 23% in the MAE7 class in 2014, to 82% in the 2017 MAE7 class (a 2.6 fold increase). The required class, SE3, also showed significant benefit to the students; there was an average increase of 18% (57% increased to 75%), and the number of "at risk" students who moved out of that category was 67%. The required SE3 class did not have as high a percentage in the "at risk" category to the elective MAE7 class in 2017 (67% vs 80%). However, this it is to be expected that an elective class would have higher gains than a required class since students taking the elective would be more motivated for self-improvement. The fact that both the elective and required classes in 2017 had high rates of effectiveness indicates that the self-selection bias of the elective class is small. In addition, the required class in 2017 required all of the SV training to be completed as homework, which is an indication of the effectiveness of the SV training app as a tool for self-guided learning.

Conclusion

SV training and specifically freehand sketching isometric and orthographic shapes, has be shown to increase graduation rates in engineering for students entering with low SV skills. However, adding new content to an already full program can be difficult. Accordingly, the potential for SV training in which students can work independently is attractive. The Spatial Vis™ app was designed to meet this need as it allows for freehand sketches to be graded automatically and for hints to be provided when needed. A prior study with the Spatial Vis™ app showed that student persistence correlated with gains in SV ability. However, the question remained as to whether it was possible to increase persistence and SV gains.

In between 2014 and 2017 the Spatial Vis™ app was redesigned to increase student engagement and effectiveness. The assignments were completely redone and gamification was added to reward persistence. Four trials were compared between 2014 and 2017 as the app improvements were implemented.

The difference between the 2014 and 2017 trial showed that indeed it is possible to increase persistence and post-test score results. The intermediate feedback of hint and use of star rewards had a large impact (it seems like college students care about stars after all). Among all groups the persistence metrics increased by 93% and among students entering the class in the Low group, the persistence metric increased by 261%.

The analysis specifically looked at students entering the class with a pre test PSVT:R score <= 70%, since these students were considered "at risk" for low graduation rates due to low SV skills. The 2014 trial has shown that these "at risk" category displayed bimodal distribution in their SV gains, and accordingly effectiveness of SV training was assessed in terms of the percentage of students that could be raised from the "at risk" category to be above it. This analysis showed a 2.6 fold (260%) increase in app training effectiveness in the elective class, MAE7. These benefits largely held up in a required class where the SV training App was used as homework, which makes it even easier to integrate into crowded curriculums.

Future work is warranted with a higher number of participants to increase the statistical significance of the findings.

Acknowledgments

We would like to thank Elizabeth Cowan for content improvements to the Spatial Vis™ app as well as figures and tables of this publication, Jon Tara for software engineering support, and Daniel Yang for analysis of the persistence data. We would also like to thank the ASEE reviewer who encouraged us to find a more rigorous metric for defining significant improvement in SV skills. In addition, a Small Business Innovation Research (SBIR) grant was awarded to eGrove Education, LLC, by the NSF (Award # 1648534), that supported the research effort of this publication.

Disclosure

Nathan Delson and Lelli Van Den Einde have equity interest in eGrove Education, Inc., a company that may potentially benefit from the research results. The terms of this arrangement have been reviewed and approved by the University of California, San Diego in accordance with its conflict of interest policies. In addition, a Small Business Innovation Research (SBIR) grant was awarded to eGrove Education, Inc., by the NSF (Award # 1648534), that also supported the research effort of this publication.

References

1. I. M. Smith, *Spatial ability: Its educational and social significance*. RR Knapp, 1964.

2. Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, *31*(3), 459-480.
3. S. A. Sorby, “Spatial Skills Training to Improve Student Success in Engineering,” in *2012 Specialist Meeting—Spatial Thinking Across the College Curriculum*, 2012, pp. 1–4.
4. S. Song and A. M. Agogino, “Insights on designers sketching activities in new product design teams,” *ASME 2004 Des. Eng. Tech. Conf.*, pp. 351–360, 2004.
5. S. Staffin Metz, C. Diane Matt, P. Campbell, J. Langeman, and R. Ribe, “Engage Engineering.” [Online]. Available: https://www.engageengineering.org/.
6. C. Hill, C. Corbett, and A. St. Rose, *Why So Few? Women in Science, Technology, Engineering, and Mathematics*. American Association of University Women, 2010.
7. S. A. Sorby, *Developing spatial thinking*. Delmar Cengage Learning, 2012.
8. R. B. Guay, *Purdue spatial visualization test: Rotations*. West Lafayette, IN: Purdue Research Foundation, 1977.
9. S. A. Sorby. "Assessment of a" new and improved" course for the development of 3-D spatial skills." *Engineering Design Graphics Journal* 69.3, 2009.
10. N. Delson and L. Van Den Einde, “Tracking student engagement with a touchscreen app for Spatial Visualization Training and freehand sketching,” *ASEE Annu. Conf. Expo. Conf. Proc.*, vol. 122nd ASEE, no. 122nd ASEE Annual Conference and Exposition: Making Value for Society, 2015.
11. N. Delson, L. Van Den Einde, E. Cowan, J. Tara “eGrove Education.” [Online] Available www.egrove.education
12. E. Hilton, M. Paige, B. Williford, W. Li, T. Hammond, and J. Linsey " Engineering Drawing for the Next Generation: Students Gaining Additional Skills in the Same Timeframe." *2017 ASEE Annual Conference & Exposition*. 2017.
13. W. Li, E. Hilton, T. Hammond, and J. Linsey. "Persketchtivity: An Intelligent Pen-Based Online Education Platform for Sketching Instruction." In *EVA*. 2016.
14. S. Vandenberg, and A. Kuse, Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and motor skills*, *47*(2), 599-604. 1978.
15. Duckworth, Angela Lee, and Lauren Eskreis-Winkler. "True grit." *APS Observer* 26, no. 4 (2013)
16. E. Cowan, N. Delson, R. Mihelich, and L. Van Den Einde, “Improvement in Freehand Sketching Application for Spatial Visualization Training,” in *Conference on Pen and Touch Technology in Education*, 2017.
17. L. Van Den Einde, N. Delson, E. Cowan, and D. Yang, “Increasing Student Persistence In A Sketching App For Spatial Visualization Training,” *ICERI2017 Proc.*, pp. 5373–5381, 2017.
18. A. K. Dean, “Applied Spatial Visualization for Engineers Applied Spatial Visualization for Engineers,” 2017.