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Implementation of a Nontraditional Spatial Skills Training Program

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Abstract

This research paper will assess the effectiveness of various approaches to building spatial skills in a remote learning environment, including the use of a sketching app and origami folding. The Purdue Spatial Visualization Test: Rotations (PSVT:R) is used to measure spatial ability before and after completion of the spatial skills training.

The importance of spatial ability in engineering is well-established and many first-year programs have been developed to help incoming students with low spatial ability build these critical skills. In our study, the spatial ability of all first year engineering students was assessed using the PSVT:R during the first week of class. A spatial skills training program was then implemented for those who scored below a threshold of 70% on the PSVT:R. Students who elected to participate in the spatial skills training program were offered two tracks, dubbed the "direct" and "indirect" approaches. The direct approach involved the use of the Spatial Vis app by eGrove Education while the indirect approach tasked students with completing origami models based on instructional diagrams. In addition to this targeted training, sketching activities that build spatial skills were also built into the graphics class for all students regardless of PSVT:R test score.

After training for 4 weeks, students were offered a midterm retake of the PSVT:R. Those that again failed to reach the threshold score of 70% were encouraged to continue with another 4 weeks of training before a final test using the PSVT:R at the end of the semester. Statistically significant increases in spatial ability were observed for students who undertook training in both the direct (n=70) and indirect (n=19) approaches. Students who did not enroll in training, but continued in the course and retook the PSVT:R (n=30) also improved their spatial ability. Similar trends were observed when broken out by gender or by initial level of spatial ability; statistically significant increases in spatial ability were observed for both female (n=55) and male (n=64) students, and for those starting out at different initial levels of spatial skill. No significant differences in the level of improvement were found between either type of training, indicating that sketching in the Spatial Vis app and folding origami are both effective methods for improving spatial ability.

Introduction

Spatial visualization (SV) skills, typically defined as the ability to visualize and solve problems in three dimensions, have been shown to be correlated with success in STEM fields [1-4]. In addition, several large scale studies have noted the importance of spatial skills in the inclusion and retention of various underrepresented groups in engineering [5-6]. Spatial skills have also proven to be malleable and various methodologies for their improvement have been shared within the engineering community [7-10]. Historically these methods have typically included workshop-style approaches completed using dedicated spatial skills curricula and accompanying resources including sketching and workbook exercises.

More recent efforts within the engineering community have developed these interventions in creative ways to better engage students, allow for self-study of spatial skills or to simply examine new methods for the improvement of spatial ability [11]. These more recent interventions include gamification via existing software such as Minecraft [12,13] as well as specifically developed tools such as the Spatial Vis smartphone app [14-16]. Other groups have examined the use of origami [17,18], sketching and building [19-21], and using other existing toys and games such as LEGO in building spatial skills. Each of these methods has proven to be effective in improving spatial ability to the extent that they are practical tools that can be used in spatial skills training.

A spatial skills assessment and training program has existed at Stevens Institute of Technology since 2016. This program is based on that developed at CU Boulder [22], itself a Montessori application of the spatial skills curriculum originally developed by Sorby [7]. As is typical of many spatial skills interventions in engineering, students are tested for their ability using the PSVT:R [23] and then complete incentivized extra-curricular workshop exercises for course credit [24]. While this methodology has proven to be successful in improving the spatial skills of students, a challenge arose in 2020 due to the outbreak of the COVID-19 pandemic during which our spatial skills assessment and training program had to be re-structured to better suit the remote learning environment.

Utilizing some of the more recent approaches to spatial skills training, we chose to partially integrate the spatial skills workshop into the engineering graphics course curriculum, rather than offer voluntary extra-curricular workshops. Short, weekly sketching exercises were assigned to the entire class in addition to asynchronous, individualized training being offered primarily to students displaying lower levels of spatial ability. Students who elected to participate in the training were offered two approaches: (1) a “direct” approach using the Spatial Vis app from eGrove Education [25], and (2), an “indirect” (no cost) approach involving the folding of various origami models. Each approach was curated by the course instructors such that student progress in improving their spatial ability was tracked.

This work describes the implementation of these approaches and aims to address the following research questions based on this methodology:

1. Was there any significant difference in improvement in spatial ability between students taking the direct and indirect approach, as measured by PSVT:R scores?

2. Were the class activities (i.e. CAD exercises, short sketching exercises) within the engineering graphics course itself effective in improving spatial ability as measured by PSVT:R test scores, i.e. did students who completed the course but not the additional training modules show significant improvements in spatial ability?
3. Were there significant differences in spatial ability, or the improvement in ability, when scores are broken down by student population (e.g. gender, initial spatial ability)?

Methods

In fall 2020, all first-year engineering students at Stevens Institute of Technology took a spatial skills test during the first week of classes in the engineering graphics course. Their spatial ability was assessed using the Purdue Spatial Visualization Test: Rotations (PSVT:R) [23], with a passing grade set at 70% (test score of 21 out of 30). Students were placed into groups based on their scores on the PSVT:R. The three placement levels were: Spatial Master – passing test score of 70% and up, Spatial Intermediate – test score of 60-69%, and Spatial Novice – test score below 60%. Students who did not initially pass the test (score 70% or more) were given the opportunity to re-take the PSVT:R in the middle of the semester and again at the end of the semester. Numerous studies [5,7,9-11] have demonstrated good test-retest reliability of the PSVT:R, using this tool as a measure of spatial ability before and after a spatial skills training intervention. In addition, the implementation of the PSVT:R in this study as an online quiz allowed for the multiple choice answers to be generated in a randomized order to further aid reliability of the test instrument.

Targeted spatial skills training was also offered to all students in the class to prepare for these retakes and incentivized by including a spatial skills component in the overall course grade. Students would earn full credit for this component by either passing the PSVT:R with a score of 21 or higher (70% or more) in any of these testing instances or by completion of the two 4-week spatial skills training modules. The inclusion of the ability to earn credit simply by participating in the workshops was a choice made to boost participation in the training and was based on prior results [24].

Students in both the spatial intermediate and novice categories were highly encouraged, but not required, to opt into the spatial skills training. Those students who chose to complete the training modules were given the option of a “direct” training approach or an “indirect” training approach. Direct training involved completing a series of sketching exercises via the Spatial Vis app [25] (approximately 16 exercises per module). The app contains a total of 9 modules, each focusing on a different visualization skill. The main benefits of this approach were gamification, personalized (instant) feedback and unlimited retries within each activity in the app. Indirect training involved selecting an origami instructional diagram of reasonable complexity (at least 10 steps) to follow and fold. Students could choose any appropriate origami instruction diagram (not video) found online. Each completed origami model counted as one training module. The main benefit of this approach was zero cost to the student, whereas a small fee is associated with the Spatial Vis app. Other benefits of the indirect (origami) approach are that it is less structured than the app and allows for much more student control and choice in the learning process. It is also a "physical"/hands-on activity that could be beneficial in improving spatial skills. Disadvantages with this method relate to the delayed and non-specific nature of feedback received as students compare their models with images rather than receiving specific guidance on where they made a mistake.

Regardless of whether they completed training or their spatial placement level, all students in the graphics class were required to complete weekly SV activity assignments, a short set of sketching exercises, as a part of the engineering graphics course.

Results

A total of 396 first-year engineering students participated in the study (109 female, 287 male). As shown in Figure 1, initial test results indicated that 66% of these students passed the PSVT:R, while 38% (n=134) needed spatial skills training (scored below 21 out of 30). These 134 students were encouraged to participate in the spatial skills training program, using either the direct (Spatial Vis) or indirect (origami) method. Of these 134 students, 75% (n=89) opted to enroll in the spatial skills training with the breakdown shown in Figure 2. Seventy students (59%) chose the direct training method and 19 (16%) chose the indirect method. The other 25% of students who "failed" the PSVT:R at the first attempt (n=30) did not elect to participate in any additional training.

Of the 134 students who scored below the 70% threshold on the initial PSVT:R, a total of 119 students took the test again mid-semester. The performance of these students on the midterm PSVT:R is compared in Table 1 and Figure 3 for the three student groups (direct, indirect and no training). All groups demonstrated a significant increase in average test score ($p < .001$), as shown in Table 1. While the greatest average gains were seen in the students who participated in the indirect training method, the differences in the gains between the three groups ($F(1,2) = 1.333$, $p = .268$) were not found to be statistically significant.

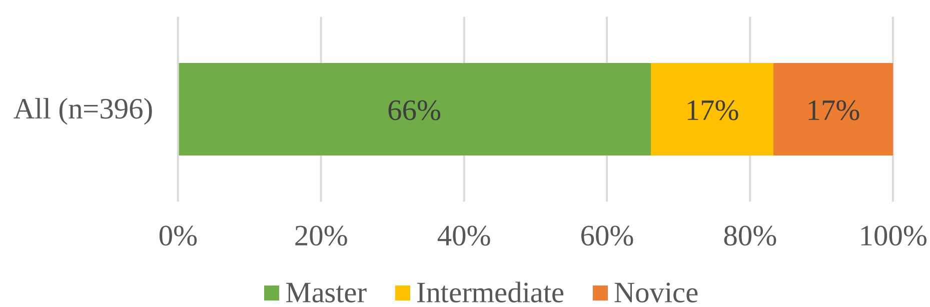

Figure 1. Initial distribution of students (%) by PSVT:R placement results (n=396)

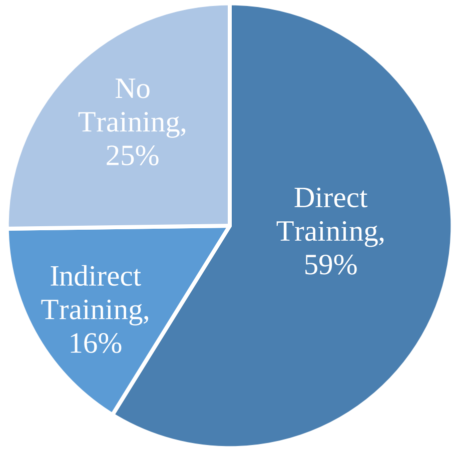

Figure 2. Student preparation for mid-semester retake (n=119)

Table 1. Descriptive statistics for initial and midterm test scores

	Initial		Midterm		
	Mean	*SD*	*Mean*	*SD*	*t-test*
Direct training	16.2	3.38	21.8	4.43	$t(70) = 10.790, p < .001$
Indirect training	17.4	2.34	24.2	3.63	$t(19) = 7.118, p < .001$
No training	17.1	2.81	21.8	3.91	$t(30) = 5.284, p < .001$

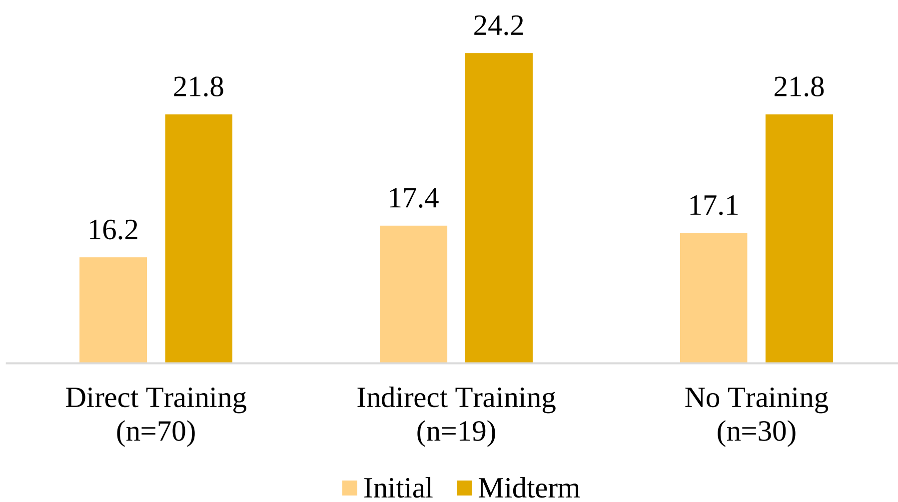

Figure 3. Average test score (out of 30) on initial and midterm PSVT:R for students who trained via direct method, trained via indirect method, and did not train

Of the 119 students who took the midterm PSVT:R, thirty-seven students again scored below the threshold score of spatial ability (21 out of 30) and were encouraged to continue with an additional four training modules. Of these 37 students, 23 chose to continue training. A total of 32 students retook the PSVT:R at the end of the semester. Twenty students continued with the direct training method, 3 students continued with the indirect method and 5 students took the final PSVT:R without additional training. Students who discontinued training or started training after the midterm are not included in this data set. No students chose to switch between training methods (direct or indirect) after the midterm.

The performance of these three groups who took the PSVT:R three times (initial, midterm, and final) is compared in Figure 4, Table 2, and Table 3. For the group that trained via direct method (n=20), a significant increase in average test score (p = .011) was observed between the initial and midterm tests, but not between the midterm and final tests. No significant increases were observed for the group who trained via the indirect method (n=3). A significant increase in average test score (p = .008) was observed between the midterm and final tests for the group who did not participate in the training program (n=5), but not between the initial and midterm tests. As shown in Table 3, the "direct training" and "no training" groups demonstrated a significant increase in average test score (p < .050) between initial and final tests, but not the "indirect training" group.

Results indicate that just 4 weeks of direct training is effective in significantly improving spatial ability. The increase in test score after an additional 4 weeks of direct training following the midterm is not statistically significant, and the average test score on the final PSVT:R is below the passing threshold. This could possibly be attributed to a lack of true effort from the students on the final test, as the completion of the 8-week training program would grant them full credit for the spatial skills component of the course, regardless of their final test score. For this reason, our incentive plan may need to be revised for future iterations to better motivate participants to put forth their best effort on the final test.

Table 2. Descriptive statistics for initial, midterm, and final test scores

	Initial		Midterm		Final	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Direct training	14.4	3.57	17.0	3.26	18.9	4.54
Indirect training	17.7	4.04	19.0	1.00	22.7	5.51
No training	18.6	3.13	18.4	3.05	24.0	2.83

Table 3. Comparative statistics for initial, midterm, and final test scores

	Initial - Midterm	Midterm - Final	Initial - Final
Direct training	$t(20) = 2.799$, $\mathbf{p = .011}$	$t(20) = 1.552$, $p = .137$	$t(20) = 3.699$, $\mathbf{p = .002}$
Indirect training	$t(3) = 0.555$, $p = .635$	$t(3) = 1.054$, $p = .403$	$t(3) = 3.273$, $p = .082$
No training	$t(5) = -0.090$, $p = .933$	$t(5) = 4.989$, $\mathbf{p = .008}$	$t(5) = 3.674$, $\mathbf{p = .021}$

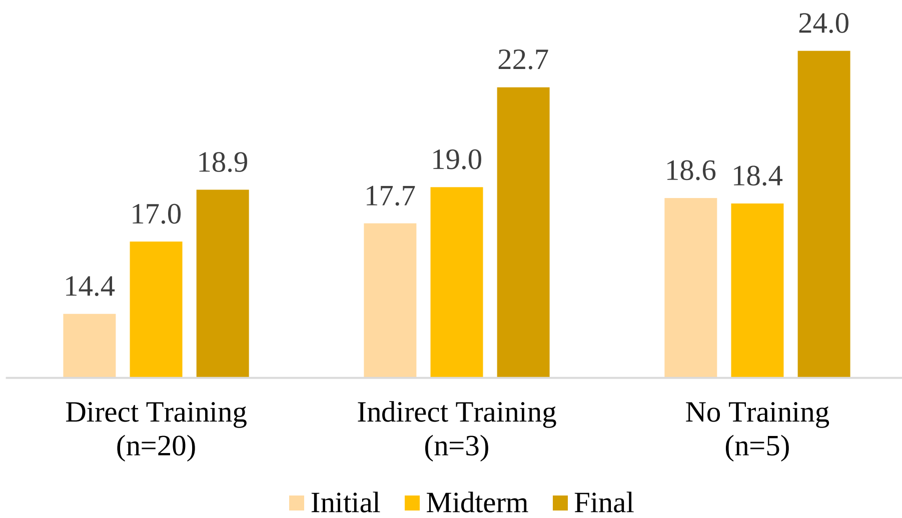

Figure 4. Average test score (out of 30) on initial, midterm, and final tests for students who trained via direct method, trained via indirect method, and did not train

The indirect training and no training groups showed modest gains from the initial to midterm tests, and larger gains from the midterm to final tests. This could indicate that these methods are only effective after a longer training period for some students. It is also possible that these training methods (indirect and simply relying on the SV activities in the class) are less rigorous than that received by students opting into the direct training. With the very small sample sizes for these two groups, however, it is difficult to make any conclusive remarks. Given the lack of significant changes when comparing midterm to final test scores for the direct and indirect approaches, it is also unlikely that students “learned” the PSVT:R and became acclimatized to the test.

Males vs. Females

Figure 1 demonstrated that the overall pass rate for the initial PSVT:R was 66%. When broken down by gender, however, it can be seen that the female pass rate was 48%, much lower than the male pass rate of 73%. This result is described in Figure 5. Significant gender differences in spatial ability have been widely reported in the literature previously [1,8]. A total of 57 females and 77 males who initially failed the PSVT:R were encouraged to participate in the spatial skills training program.

There were 55 females and 64 males who chose to retake the PSVT:R mid-semester. Prior to the retake, 82% (n=45) of these females participated in some form of training, while only 69% (n=44) of males chose to participate in the training, as shown in Figure 6. In both groups, the majority of students chose to use the direct training method.

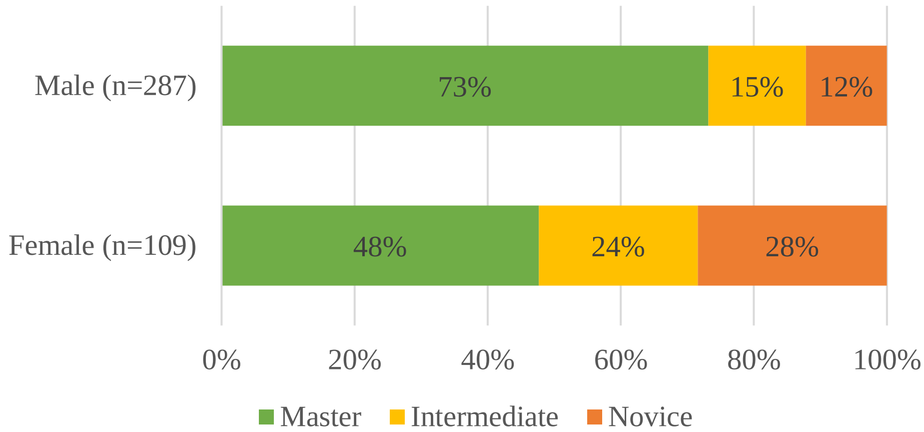

Figure 5. Initial placement results, by gender

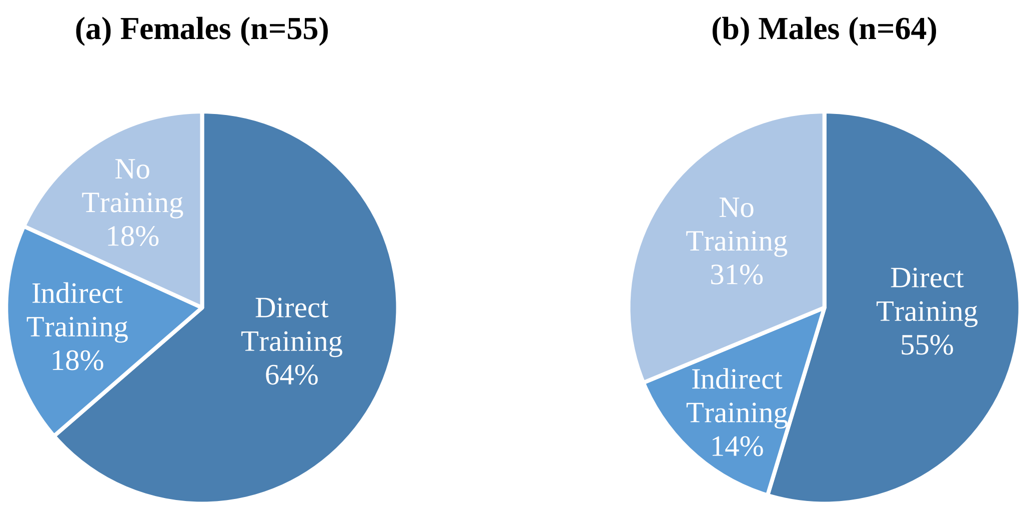

Figure 6. Student preparation for mid-semester retake by (a) females (n=55) and (b) males (n=64)

Figure 7 breaks down the initial and midterm PSVT:R scores by gender and training method. Similar trends for females and males were observed among each of the three groups: students who trained via the direct method, trained via the indirect method, and did not train. Scores for all groups increased significantly from the initial to the midterm tests ($p < .010$), as seen in Tables 4 and 5. As shown in Figure 3, but now broken out by gender, both male and female students made the largest gains when trained using the indirect (origami) approach however the differences in gains between the three training methods were not found to be statistically significant for females ($F(1,2) = 0.359$, $p = .700$) or for males ($F(1,2) = 0.811$, $p = .449$).

Table 4. Descriptive statistics for initial and midterm test scores among females

Females	Initial		Midterm		
	Mean	*SD*	*Mean*	*SD*	*t-test*
Direct training	15.4	3.57	21.6	4.69	$t(35) = 7.702, p < .001$
Indirect training	17.3	2.36	24.3	4.27	$t(10) = 4.869, p = .001$
No training	17.1	2.73	22.3	4.00	$t(10) = 3.299, p = .009$

Table 5. Descriptive statistics for initial and midterm test scores among males

Males	Initial		Midterm		
	Mean	*SD*	*Mean*	*SD*	*t-test*
Direct training	17.0	3.01	22.0	4.20	$t(20) = 4.040, p = .001$
Indirect training	17.6	2.46	24.1	3.02	$t(35) = 7.674, p < .001$
No training	17.2	2.92	21.6	3.94	$t(9) = 4.991, p = .001$

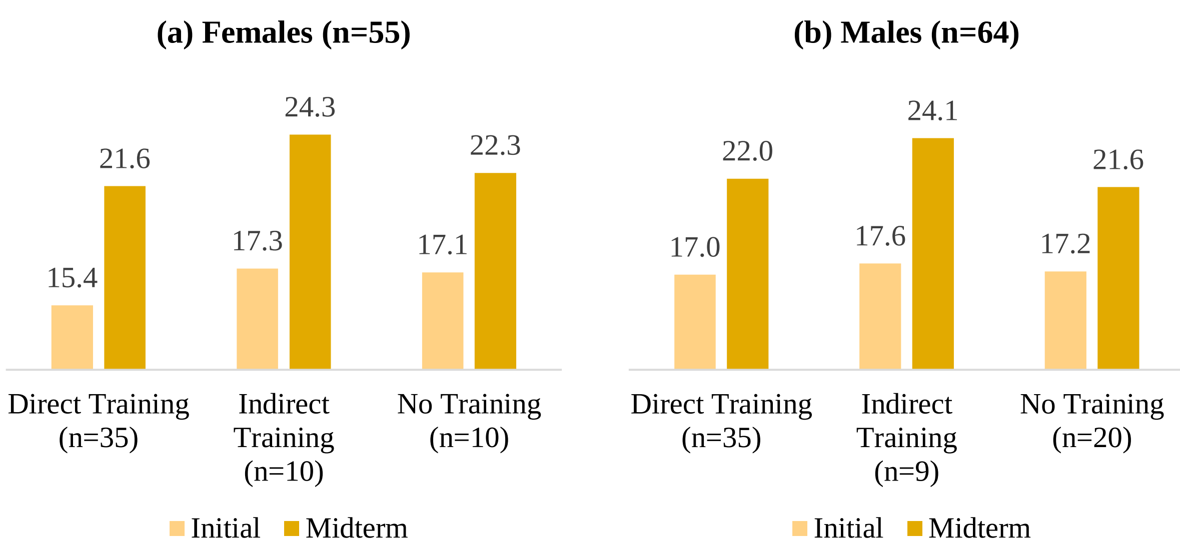

Figure 7. Average test score (out of 30) on initial and midterm tests for (a) female (n=55) and (b) male (n=64) students who trained via direct method, trained via indirect method, and did not train.

Although female students were more likely to participate in training than their male counterparts, both groups displayed similar preferences in training method (for the direct approach - see Figure 6), and their average test scores significantly improved for each training category (see Figure 7). No significant differences between training methods were observed for females or males (see Tables 4 & 5).

Novices vs. Intermediates

There were 61 Spatial Novices and 58 Spatial Intermediates who chose to retake the PSVT:R mid-semester. Prior to the retake, 74% (n=45) of Novices participated in some form of training, and 76% (n=44) of Intermediates chose to participate in the training, as shown in Figure 8. In both groups, the majority of students chose to use the direct training method.

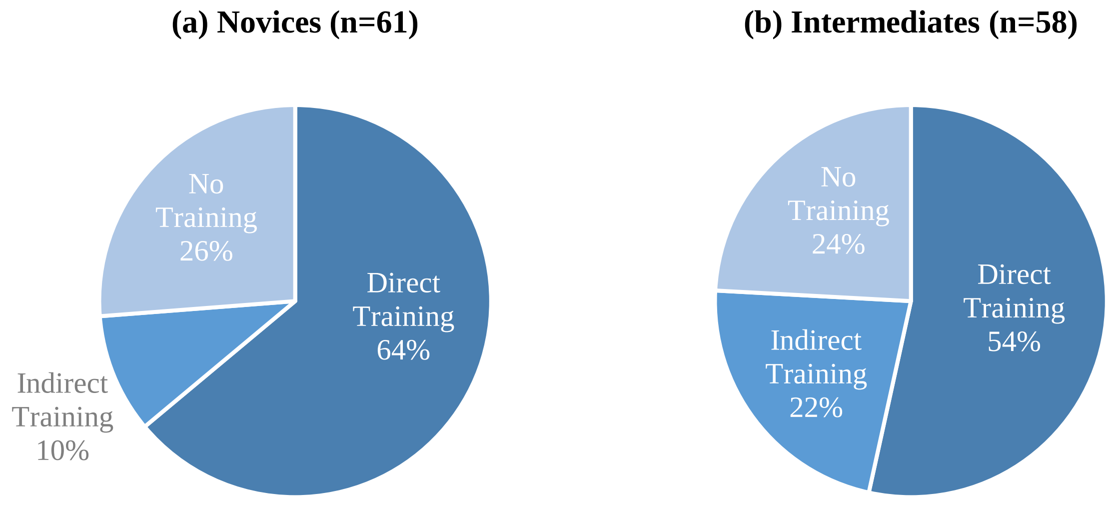

Figure 8. Student preparation for mid-semester retake by (a) Novices (n=61) and (b) Intermediates (n=58)

As shown in Figure 9, an increase in average test score was observed among each of the three training regimes, for both Novices and Intermediates. Tables 6 and 7 show that PSVT:R scores for all groups increased significantly from the initial to the midterm tests ($p < .001$), except for the group of Intermediates who did not participate in any training program ($p = .062$). As discussed previously, the largest gains were made with the indirect (origami) approach but were not found to be statistically significant for Novices ($F(1,2) = 0.766$, $p = .474$) or for Intermediates ($F(1,2) = 2.842$, $p = .067$).

Results show statistically significant improvements in spatial ability for both Novices and Intermediates who participated in either direct or indirect training. Increases in average test score were statistically significant for Novices who did not participate in any training program but were not significant for Intermediates who did not train. This result indicates that additional training may be necessary to improve spatial skills for students beyond an intermediate level. Novices appear to benefit from the small set of weekly spatial skills activities completed during the Graphics course, achieving an average test score (M=21.9, SD=4.11) comparable to those of Intermediates (M=21.7, SD=3.81) by mid-semester. Strangely, novices who received no training had a higher average test score than those who participated in direct training. Upon closer inspection, those who participated in direct training started from a lower average test score, and both groups achieved a very similar average gain of 6.8 points.

Table 6. Descriptive statistics for initial and midterm test scores among spatial novices

Novices	Initial		Midterm		
	Mean	*SD*	*Mean*	*SD*	*t-test*
Direct training	13.8	2.71	20.6	4.63	$t(39) = 8.997, p < .001$
Indirect training	14.5	1.64	23.7	3.61	$t(6) = 8.507, p < .001$
No training	15.1	2.24	21.9	4.11	$t(16) = 6.029, p < .001$

Table 7. Descriptive statistics for initial and midterm test scores among spatial intermediates

Intermediates	Initial		Midterm		
	Mean	*SD*	*Mean*	*SD*	*t-test*
Direct training	19.1	0.85	23.3	3.69	$t(31) = 6.732, p < .001$
Indirect training	18.8	0.93	24.5	3.76	$t(13) = 4.721, p < .001$
No training	19.5	0.76	21.7	3.81	$t(14) = 2.040, p = .062$

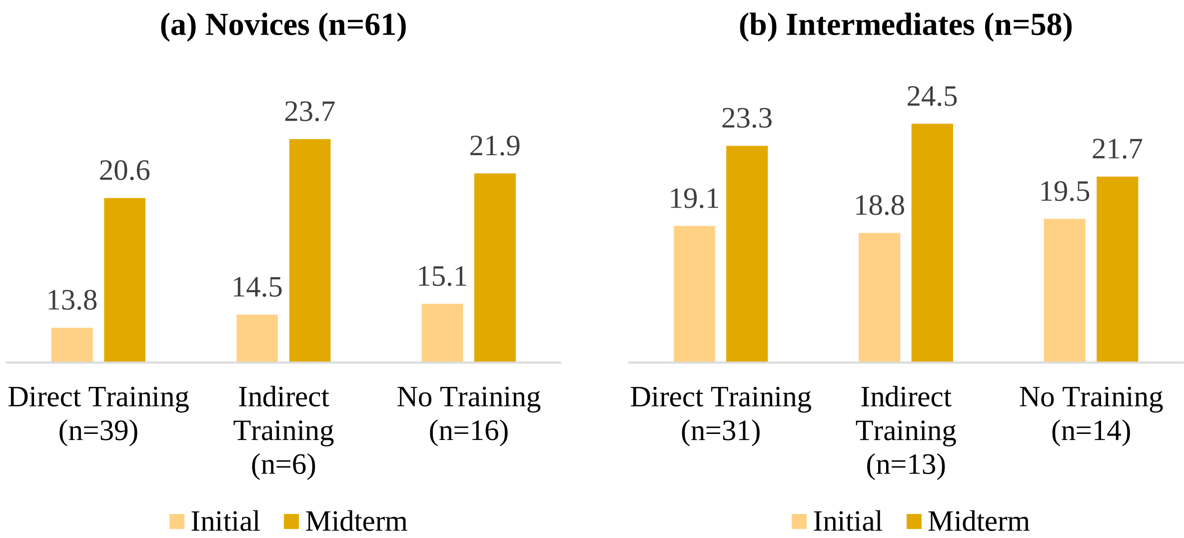

Figure 9. Average test score (out of 30) on initial and midterm tests for (a) Novices (n=61) and (b) Intermediates (n=58) students who trained via direct method, trained via indirect method, and did not train.

In terms of which training method was the most beneficial for improving spatial ability, the differences in the gains made between groups undergoing different training methods was not statistically significant when broken down by gender or initial level of spatial ability. A larger sample size is perhaps required to better assess this question as fewer students were sampled in both the “indirect” (n=19) and “no training” (n=30) groups. The larger gains made by students in the indirect group, while not statistically different to the gains made by students in the other groups, are however interesting. Serrano et al. [17] demonstrated in their work that a combination of CAD exercises and origami folding was more beneficial to improving spatial ability than either method in isolation. It is possible that a larger data set here could support these results as the students in the indirect method employed here utilized origami to improve the SV and our graphics course is heavily focused on the use of CAD tools.

Qualitative Student Feedback on Training Methods

As shown in Figure 2, the majority of students who initially did not pass the test (119 of 134) chose to participate in the additional spatial skills training program, either through sketching exercises on the Spatial Vis app (direct method, n=70) or folding origami models (indirect method, n=19). Students who did not participate in any training program (n=30) still received some opportunities to build their spatial skills through in-class spatial visualization (SV) activities that were assigned to all students enrolled in the graphics course. These in-class SV activities involved focused sketching exercises as well as freehand sketching tasks.

Following the completion of the study described here, students were asked to give their feedback on the spatial skills exercises they participated in via an online survey. A Likert rating scale was used as follows with the survey items described in Table 8: 1-Strongly Disagree, 2-Disagree, 3-Neither agree nor disagree, 4-Agree, 5-Strongly Agree. Table 8 also shows a summary of the results along with the overall average score in each category.

Students felt that all the spatial skills exercises helped to improve their spatial ability, with the sketching exercises on the Spatial Vis app ranked the most effective. The origami exercises were ranked as the most challenging, with the Spatial Vis app exercises ranked the least challenging. The origami exercises were also ranked as the most enjoyable, with the in-class SV activities ranked as the least enjoyable.

Table 8. Student Responses to Spatial Skills Survey Items

	Direct Method (n=37)	Indirect Method (n=9)	In-Class SV Activities (n=50)
These exercises improved my spatial skills.	4.30	4.22	4.16
These exercises were challenging.	3.68	4.44	4.40
These exercises were enjoyable.	3.78	4.44	3.46

Conclusions

Spatial skills are known to be strongly correlated with success and persistence in STEM. Spatial skills training programs of various natures have proven to be effective in improving the spatial ability of students and are known to be of particular benefit to women and other under-represented groups.

A spatial skills program has existed at Stevens Institute of Technology as part of the first-year graphics course since 2016. This past academic year, the program was modified to incorporate recent practices and tools used in spatial skills training. All incoming first year students were assessed in terms of their spatial ability using the Purdue Spatial Visualization Test: Rotations (PSVT:R). Students were divided into three groups: Spatial Master, Spatial Intermediate and Spatial Novice. Spatial Masters scored at least 21 out of 30 on the PSVT:R and were deemed to have “passed the test” Students in the other groups were encouraged to enroll in spatial skills training using one of two approaches. Students could choose to either study spatial skills using the Spatial Vis app, deemed the “direct” approach or via an “indirect” approach by folding origami. All students were also given several spatial skills exercises as part of the graphics class. Students were then retested for the spatial ability using the PSVT:R at the middle and end of the semester to examine their improvement.

Statistically significant increases in spatial ability were observed for students who undertook training in both the direct (n=70) and indirect (n=19) approaches. Students who did not enroll in training, but continued in the course and retook the PSVT:R (n=30) also improved their spatial ability. It is likely that these students benefitted from the sketching exercises that were assigned to the whole class as well as the nature of the graphics class itself acting as a training mechanism.

Similar trends were observed when broken out by gender; statistically significant increases in spatial ability were observed for both female (n=55) and male (n=64) students under all three training groups (direct method, indirect method, and no training). No gender-specific trends were observed, indicating that no particular training method appeared to be more effective for females vs. males.

Novices (n=61) in the direct training, indirect training and no training groups all significantly improved their spatial ability. Significant improvements in spatial ability were also observed for Intermediates (n=58) in the direct and indirect training groups, but not in the group that did not participate in the training program. This indicates that while the weekly sketching exercises assigned in the graphics course served to improve the spatial skills of Novices, the rigor of a training program (direct or indirect) may be required to improve spatial ability beyond an Intermediate level.

While the greatest average gains in spatial ability were seen in students who undertook the “origami” (indirect) approach, all students improved their spatial ability and the changes in any one approach were not found to have a greater statistical significance. Still, prior work has shown that a combination of CAD and origami is a more effective approach in developing spatial skills than either method alone. In their feedback regarding the interventions, students also rated the origami-based approach as both more challenging and more enjoyable than the other methods. Such “challenge” and motivation are important components of the voluntary workshop that need to be further considered. Moving forward, it would be interesting to assess the effect of a mixed-methods approach (CAD/origami) in our context and to develop a larger sample using the indirect (origami) method (n=19 in this study).

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