Longitudinal Study of Student Performance after an Optional Supplemental Course to Enhance Spatial Visualization Skills in First-Year Engineering Students

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Abstract - **The impact of spatial visualization skills on retention and performance in undergraduate engineering schools has been studied extensively. Michigan Technological University began researching strategies to improve spatial visualization skills in the early 1990's. One research-proven strategy to increase retention and GPA in freshman engineering students is to improve students' spatial visualization skills. With this goal in mind, we have developed an optional one-credit hour non-graded spatial visualization skills intervention course which is offered to incoming freshman engineering students based on their performance on the Purdue Spatial Visualization Test: Rotations (PSVT:R). We are now assessing the long-term impact of this course on student visualization skills and asking the question "*Can an optional one-credit hour spatial visualization intervention class be used as an effective instructional tool that enables students to enhance their spatial visualization skills and long-term performance in engineering?*"**

The research design is quasi-experimental with control and treatment groups where the treatment group, which scores an 18 or below on the PSVT:R which is taken by all entering engineering students at summer orientation, opts to takes the intervention course. The intervention course is a 1-credit hour non-graded visualization intervention class that offers exercises designed to help students improve their visualization skills which supports their ability to perform well in engineering graphics. The control group are the students who score an 18 or below on the PSVT:R but opt out of taking the intervention course and enroll directly in the first-year engineering courses.

We report on the control and experimental cohorts from 2011 with current enrollment status and academic performance. Based on the literature, we hypothesize that students who took the intervention class will perform better in their first-year engineering classes as well as overall academically when compared to the control group. This paper details our findings to date.

Index Terms – Purdue Spatial Visualization Test: Rotations, Retention, Spatial Visualization.

INTRODUCTION

The number of individuals entering engineering programs at the post-secondary level and pursuing engineering careers has increased somewhat in recent years [1]. However, the rapidly growing need for capable engineers far outpaces the number of individuals currently pursuing, or intending to pursue, engineering as a career [2]. Moreover, females and members of other historically marginalized groups remain drastically under-represented in most domains of engineering [3]. This study focuses on two aspects of recent efforts to address the issue: (1) increasing and diversifying the number of participants in engineering and (2) increasing the spatial visualization skills of individuals belonging to underrepresented minority groups and who may choose to enter the engineering workforce. In a longitudinal study of 400,000 American high school students, students' spatial visualization abilities were found to be strongly associated with the acquisition of higher degrees and occupational credentials in STEM, and in fact its importance grows greater with higher academic degrees [4]. Moreover, this same study found that current methods for identifying students with great potential, which often focus on verbal and mathematical abilities, often miss individuals with high capabilities in spatial ability, creating an overlooked population with talent [4]. Strategies to successfully teach spatial skills include the use of multiple concurrent approaches and mediums to teaching, allowing students to make cognitive connections between multiple representations [5][6]. For example, Mayer and Anderson found that the problem solving ability of students who watched a concurrent animation and narration of the mechanical workings of a bicycle tire pump or automotive braking system was significantly better than those who had received narration before or after watching the animation [6]. Significantly, Sanchez and Wiley found that the addition of animations to the explanation of a scientific concept (plate tectonics) eliminated the differences in spatial ability, interest, and learning [7]. Supplemental classes for students who scored lower on spatial visualization testing have been found to lead to statistically significant gains in a post-course test evaluation, even if only a segment of the supplemental material was taught [8].

The National Science Foundation funded a five-year program called "Engaging Students in Engineering" or ENGAGE. One strategy in ENGAGE is to improve students' spatial visualization skills. With this goal in mind, we have developed an optional one-credit hour non-graded spatial visualization skills intervention course which is offered to incoming first-year engineering students based on their performance on the Purdue Spatial Visualization Test: Rotations (PSVT:R). We are now assessing the impact of this course on student visualization skills and asking the question "*Can an optional one-credit hour spatial visualization intervention class be used as an effective instructional tool that enables students to enhance their spatial visualization skills and long-term performance in engineering?*"

RESEARCH DESIGN

The research design is quasi-experimental with control and treatment groups. The treatment group (TG) are the incoming freshman engineering class of autumn 2011 students who score 18 or below on the PSVT:R and opt to take the intervention course. The control group (CG) are students entering in engineering in the same term who also score an 18 or below on the PSVT:R but opt out of taking the intervention course and enroll directly in the first-year engineering courses. The CG are matched to the TG by honors/scholars rank, gender, ethnicity, 1st generation status, and pre-PSVT:R score. An attempt was made to match engineering major as closely as possible.

The intervention course is a one-credit hour non-graded visualization class that offers additional representations of objects to be depicted in assigned engineering graphics drawing problems. All entering engineering students are encouraged to take the PSVT:R during summer orientation. Based on the literature, we hypothesize that students who take the intervention class will perform better in their first-year engineering classes as well as overall academically when compared to the control group. There were 1614 entering engineering freshman autumn 2011. Of those, 867 chose to take the PSVT:R with the mean score being 23.5 for this group.

From this group 138 (15.9%) scored an 18 or below and were encouraged to take the optional one-credit hour non-graded (pass/fail) course. Two sections of ENGR 180 were offered AU 2011 with 45 students enrolling in the course (Treatment Group). The control group was matched to the TG from the remaining students. The demographics of the TG and CG are listed in Table 1. The detailed structure of the optional intervention course has been previously reported [9]. Briefly, students sat four to a table where a computer was available to each student at the table. Students used a workbook and tactile modeling sets to represent a 3-D object using a coded plan in addition to other exercises. Goals include being able to create isometric and orthogonal sketches, create sketches of solid objects by combining them with other solid objects or revolving them about one or more axes, and represent a 3-D object by "unfolding" it and sketching a flat pattern on paper or computer screen. The last learning objective is to be able to create the sketch of an object reflected and shown as a sectioned view.

Data were collected on both TG and CG from AU 2011 through SP 2015 as allowed by our Institutional Review Board Protocol #2013B0358.

TABLE I
DEMOGRAPHICS OF TG AND CG

2011 Cohort (45/group)		TG	CG
Female		20 (44.4%)	20 (44.4%)
Honors Status		1 (2.2%)	1 (2.2%)
Scholars Status		2 (4.4%)	2 (4.4%)
Ethnicity	Asian	2 (4.4%)	3 (6.6%)
	Black or African	3 (6.6%)	3 (6.6%)
	Hispanic	2 (4.4%)	2 (4.4%)
	None Given	1 (2.2%)	0
	Two or More	3 (6.6%)	2 (4.4%)
	White	34 (75.6%)	35 (77.8%)
1st Generation		8 (17.8%)	9 (20.0%)
Eng. Major	Aviation	1 (2.2%)	2 (4.4%)
	Biomed	7 (15.6)	10 (22.2%)
	Chemical	5 (11.1%)	5 (11.1%)
	Civil	5 (11.1%)	3 (6.6%)
	Computer Science	3 (6.6%)	2 (4.4%)
	Electrical & Computer	2 (4.4%)	4 (8.8%)
	Eng - pre	10 (22.2%)	10 (22.2%)
	Environmental	5 (11.1%)	1 (2.2%)
	Industrial Systems	3 (6.6%)	0
	Mechanical	4 (8.8%)	8 (17.8%)

RESULTS

The following section reports on the findings of this study.

I. Academic Performance

Academic performance of the groups indicated by total cumulative grade point average (GPA) and total cumulative earned credit hours (Total Credit Hours) along with pre-PSVT:R performance for each student was collected. Averages +/- standard deviations are shown in Table II and also graphically in Figures 1-3. Statistically significant differences were found between the TG and CG for both cumulative GPA and total credit hours at the p <

0.05 level. There was no statistical difference between the pre-PSVT scores for both groups.

TABLE II
SUMMARY OF ACADEMIC PERFORMACE BETWEEN AU 2011 AND SP 2015 BY PSVT:R

2011 Cohort	Cumulative GPA	Total Credit Hours	Pre-PSVT Score
TG	2.98 +/- 0.40	104.4 +/- 9.9	15.93 +/- 4.37
CG	2.73 +/- 0.44	99.9 +/- 10.5	17.75 +/- 4.73
p-value	0.007*	0.03*	0.14
* Denotes significance at p < 0.05 level			

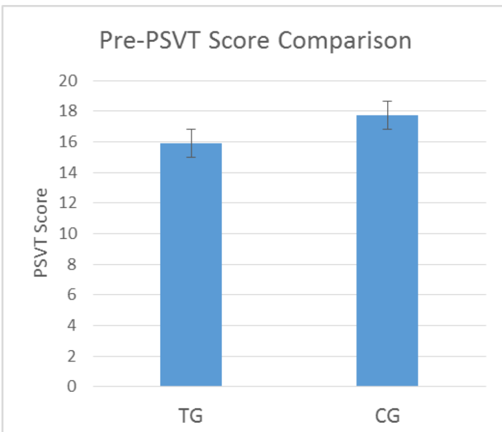

FIGURE 1
COMPARISON OF PRE-PSVT:R SCORES BETWEEN TG AND CG.

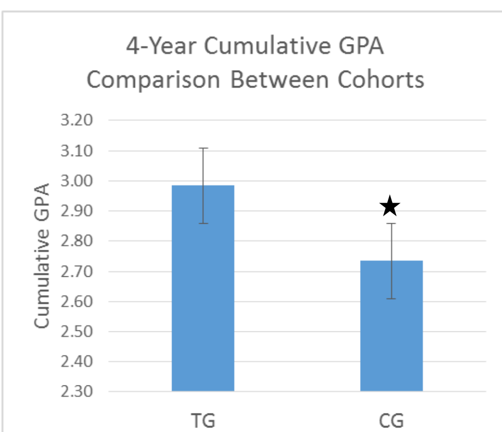

FIGURE 2
COMPARISON OF CUMULATIVE GPA FROM AU2011 TO SP 2015.
★ = P < 0.01

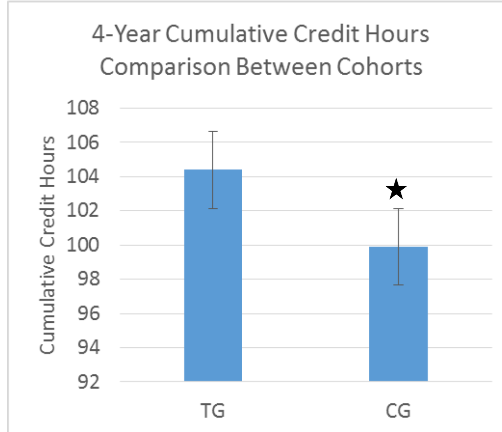

FIGURE 3
COMPARISON OF CUMULATIVE EARNED CREDIT HOURS FROM AU2011 TO SP 2015 ★ =P < 0.05.

II. Retention and Graduation Rates

As a measure of the effectiveness of the spatial visualization intervention course, we examined student retention and graduation rates. The students in this study matriculated at this university AU 2011 and we looked at the data in SP 2015 term. For this analysis, we designated as "retained" anyone who had either graduated from or was still enrolled in the institution in any major. We also examined whether or not the students had either graduated from or were still enrolled in engineering. Figure 4 presents the data from this analysis. The differences between retention in engineering and number of students who withdrew were highly statistically significant between the TG and CG.

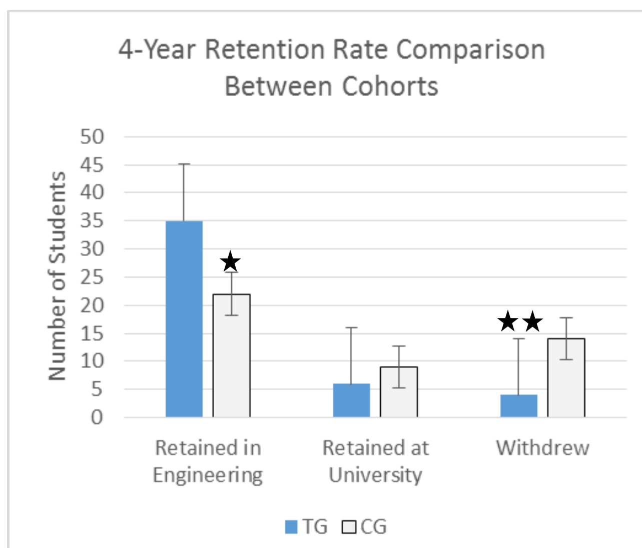

FIGURE 4
COMPARISON OF RETENTION RATES AFTER FOUR YEARS.
★ = P < 0.00001; ★★ =P<0.0005

Further analysis of the current academic plan compared to the initial academic plan upon enrollment in 2011 revealed that 26.7% of the TG engineering students changed engineering major, and only 20% of the CG changed to another engineering major. These data are shown in Table III for the TG and Table IV for the CG.

Another measure of academic success (or lack thereof) is the number of times that a STEM course, as defined as all of the following introductory courses: Pre-calculus, Calculus I, Physics I, Chemistry I, Engineering I, and Engineering II were taken and passed. Counts were made in two categories, first, if any of these courses was repeated only one time, and second, if any of these courses was repeated multiple times. These data are shown in Figure 5 showing that 15 TG students repeated one course while only 12 CG students repeated only one course. However, 11 TG repeated more than one course while 17 CG students repeated more than one of these STEM courses.

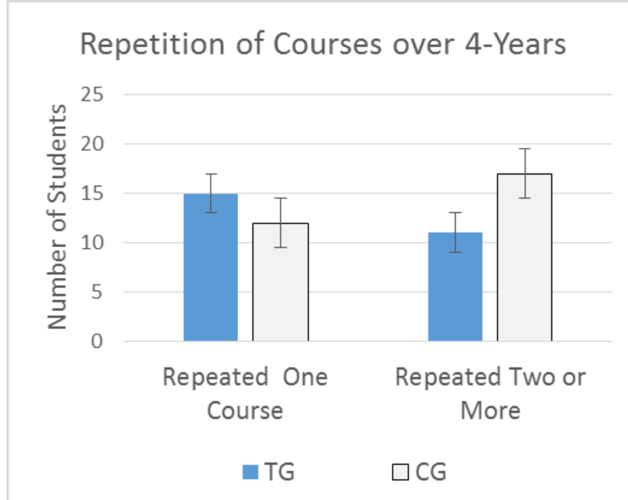

FIGURE 5
ENGINEERING COURSE REPETITION RATES OF TG AND CG.

TABLE III
SUMMARY OF ACADEMIC PLAN CHANGES BETWEEN AU 2011 AND SP 2015 FOR TG

2011 Cohort Majors		TG AU2011	TG SP2015
Eng. Major	Architecture	0	2 (4.4%)
	Aviation	1 (2.2%)	2 (4.4%)
	Biomed	7 (15.6)	1 (2.2%)
	Chemical	5 (11.1%)	7 (15.6)
	Civil	5 (11.1%)	4 (8.8%)
	Computer Science	3 (6.6%)	1 (2.2%)
	Electrical & Computer	2 (4.4%)	1 (2.2%)
	Eng Physics	0	1 (2.2%)
	Eng - pre	10 (22.2%)	0
	Environmental	5 (11.1%)	3 (6.6%)
	Geographic Info Science	0	1 (2.2%)
	Industrial Systems	3 (6.6%)	6 (13.3%)
	Material Science	0	2 (4.4%)
	Mechanical	4 (8.8%)	1 (2.2%)
	Welding Eng	0	2 (4.4%)
	Re-Exploring Engineering	0	1 (2.2%)
Non-Eng Major	Economics	0	1 (2.2%)
	Environmental Policy	0	1 (2.2%)
	Finance	0	1 (2.2%)
	Political Science	0	1 (2.2%)
	Psychology	0	1 (2.2%)
	Zoology	0	1 (2.2%)
Withdrew		0	4 (8.8%)

TABLE IV
SUMMARY OF ACADEMIC PLAN CHANGES BETWEEN AU 2011 AND SP 2015 FOR CG

2011 Cohort Majors		CG AU2011	CG SP2015
Eng. Major	Architecture	0	0
	Aviation	2 (4.4%)	1 (2.2%)
	Biomed	10 (22.2%)	1 (2.2%)
	Chemical	5 (11.1%)	2 (4.4%)
	Civil	3 (6.6%)	2 (4.4%)
	Computer Information Sci	0	2 (4.4%)
	Computer Science	2 (4.4%)	1 (2.2%)
	Electrical & Computer	4 (8.8%)	1 (2.2%)
	Eng - pre	10 (22.2%)	0
	Environmental	1 (2.2%)	0
	Food, Ag & Biological Eng	0	3 (6.6%)
	Geographic Info Science	0	1 (2.2%)
	Industrial Systems	0	1 (2.2%)
	Material Science	0	1 (2.2%)
	Mechanical	8 (17.8%)	4 (8.8%)
	Welding Eng	0	1 (2.2%)
	Re-Exploring Engineering	0	1 (2.2%)
Non-Eng Major	Atmospheric Science	0	1 (2.2%)
	Biology	0	1 (2.2%)
	English	0	1 (2.2%)
	Hospitality Management	0	1 (2.2%)
	Molecular Genetics	0	1 (2.2%)
	Political Science	0	1 (2.2%)
	Psychology - BA	0	1 (2.2%)
	Psychology - BS	0	1 (2.2%)
	Radiation Science	0	1 (2.2%)
Withdrew		0	14 (31.1%)

DISCUSSION

The data presented in the preceding paragraphs focuses on engineering freshmen who began their academic career behind the majority of their peers due to below average spatial visualization skills as indicated by their score on the PSVT:R. In 2011 taking the PSVT:R was an optional requirement for incoming first-year engineering students, with only 50.5% of the incoming class opting to participate. Of these students, 15.9% scored at or below 18 out of 30 on the PSVT:R, shown in numerous studies to be linked to performance in mathematics and other courses heavily based on mathematics such as Physics, Chemistry and Engineering courses. [10]

We have previously reported on the typical demographics of students who begin their academic career with below average spatial visualization skills highlighting the fact that even though the general student population is generally around 20% female, greater than 40% of the incoming population with below average spatial visualization skills is female. [9] In addition, the ethnic differences are also marked with the general incoming freshman class being around 70% white, while there are only about 20% white who score below 18 on the PSVT:R. This means that the majority of the students who need improvement in their spatial visualization skills are the minority gender-wise and ethnically. [9]

In order to match the control group as closely as possible to the treatment group, multiple demographic parameters were controlled as closely as possible. These include gender, ethnicity, honors/scholars ranking, first generation status, PSVT:R score, and academic plan of admission. These data are shown in Table I for both groups with no statistical differences between groups.

The findings definitely support previous work which confirms a relationship between spatial visualization skills and performance in mathematics and engineering. [10] With no difference in pre-PSVT:R average scores between the groups, the TG performed better academically in terms of higher cumulative GPA of 2.98 vs. 2.73 for the CG ($p = 0.007$), more total credit hours over the four year of college for TG of 104.4 vs. 99.9 for the CG ($p = 0.03$), higher retention in engineering majors of 77.8% for TG vs. 48.9% for CG ($p < 0.00001$), higher overall retention in university for TG of 91.1% vs. 68.9% for CG ($p < 0.0005$), and fewer withdrawals from university ($p<0.0005$). These are strong evidence that spatial visualization skills are linked to success in mathematics and engineering.

Another interesting statistic that can be drawn from the analysis is the number of students that changed engineering majors from each group. Twelve students (26.7%) from the TG changed majors within engineering while only nine (20%) changed engineering majors in the CG. This might indicate a level of introspective analysis on the TG, or possibly this is simply an artifact of the self-selection process that is used to enroll students in the optional intervention course.

In addition, one can study the number of times that any of the STEM courses, Pre-calculus, Calculus I, Physics I, Chemistry I, Engineering I, and Engineering II are repeated for a passing grade. The 15 students in the TG repeated one of these courses one time while 12 students in the CG repeated one course. However, only 11 students in the TG repeated one of the STEM courses more than once while 17 CG students had to repeat one of the STEM courses more than once. This may also be interpreted as more TG students were successful in these STEM courses the first time, or with one repetition, while it took more CG students multiple tries to become successful in the same STEM courses.

Overall, these data strongly support the hypothesis that a one credit-hour, optional, non-graded (pass/fail) spatial visualization intervention course *CAN* be used as an effective instructional tool to enable students to enhance their spatial visualization skills *AND* long-term performance in engineering. These improvements are inherently focused on females and URM populations simply by the rate at which these populations matriculate with below average spatial visualization skills.

Further improvements in the process can be made in the future including requiring all incoming first-year engineering students to take the PSVT:R at or before orientation, making the spatial visualization course graded, and automatically enrolling students who score 18 or below on the PSVT:R into the spatial visualization intervention course thus requiring them to opt out if they choose not to take the course.

Future research includes further analysis of a larger group of students over a longer period of time to facilitate disaggregating by demographic factors.

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