Initial Investigations into Spatial Skills as Predictors of Success in First-year STEM Programmes

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INTRODUCTION

Through numerous research studies conducted over the past fifty years, the importance of well-developed 3-D spatial skills for success in engineering and other STEM fields has been widely demonstrated. Research conducted in the U.S. and elsewhere, has demonstrated the high level of 3-D spatial skills found in engineering students; however, not all of our first-year students have strong spatial skills when they start their post-secondary studies. Poor spatial skills put these students at a distinct disadvantage when completing introductory courses in mathematics, CAD, descriptive geometry, and graphic communications - first-year requirements in many engineering and STEM programs. In turn, this often leads to poor grades and dropping out of engineering as a result. Women are disproportionally among the group of students with weak 3-D spatial skills. In this study, the spatial skills of first-year students in several engineering and technology programs were assessed through use of two standardized instruments widely used in spatial cognition research. At this interim stage of the research, only grades from the end of semester 1 were available. Results from several key courses were examined to determine if there is a link between spatial skill level and student performance in these courses. This paper outlines the results obtained from this study and draws conclusions regarding the importance of spatial skills for success in introductory STEM courses.

1 BACKGROUND

1.1 Prior work in Spatial Cognition

Constructing three-dimensional objects from two-dimensional drawings is a typical example of a cognitive process required in engineering where spatial-visualisation information is interpreted by the brain. Research has shown the importance of spatial skills and highlighted its contribution to performance in science, technology, engineering and mathematics (STEM) disciplines as well as using it as a predictor of achievement [1] [2] and as an indicator of student retention [3] [4].

1.2 Tests of Spatial Cognition

Several tests have been developed through the years designed to assess an individual's spatial skills in a number of areas: spatial perception; spatial visualization; mental rotations; spatial rotations and spatial orientation [5]. In this study, two specific tests were used to assess spatial skills. The first was a test of mental rotation, the Purdue Spatial Visualization Test: Rotations (PSVT:R) [6]. For the items on this test, an object is shown on the top line which has been rotated in space by a given amount. A second object is shown on the next line and the test taker must mentally rotate this second object by the same amount and choose the correct view from the third line of the problem. An example problem from the PSVT:R is shown in Figure 1.

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The second test of spatial visualization used in this study was the Mental Cutting Test (MCT) [7]. This test was first used as part of a college entrance exam in the U.S. in 1939 and measures a person's ability to imagine the cross-section of an object that has been sliced by an angled cutting plane. With this test and object and cutting plane line are presented and the participant must select the correct cross-section from those given. Figure 2 shows an example problem from MCT.

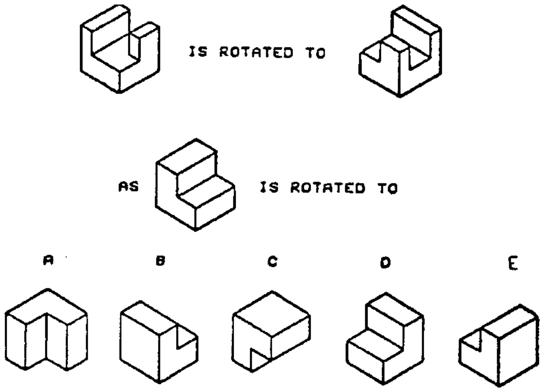

Fig. 1. Example problem from PSVT:R
(Correct answer=D)

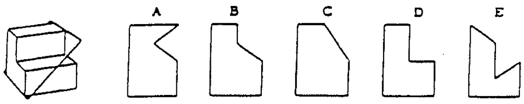

Fig. 2. Example problem from MCT
(Correct answer=D)

1.3 Irish Context

The standard route of entry to third level education in Ireland is through the Central Applications Office (CAO). Entry to a programme is dependent on a student's results in a senior state examination known as the Leaving Certificate (LC) which takes place at the end of their final year in secondary school. Points are awarded based on a student's performance in their best six subjects. The minimum point's level for a programme is determined by student demand and the limited number of places available.

The Dublin Institute of Technology (DIT) is the largest third level institute in Ireland with in excess of 22,000 undergraduate students. There are two levels of engineering degrees in Ireland - the Ordinary Degree (three years, Level 7) and the Honours degree (four years, Level 8). In DIT entry to Level 8 engineering programmes (BE) require the student to have a high mathematical ability with a minimum of a grade C (55%) in a higher level mathematics exam in the LC. Entry to most Level 7 engineering programmes (B. Eng. Tech.) requires a minimum of a grade D (40%) in a lower level mathematics exam. Students on Level 8 engineering programmes tend to have a higher academic ability in mathematics than those on Level 7 engineering programmes.

The typical route to both Honours and Ordinary engineering programs in DIT is illustrated in Figure 3. Courses are generally delivered over 1 or 2 semesters which with each semester comprising of 13 weeks of contact, 1 week for review and 2 weeks for examinations.

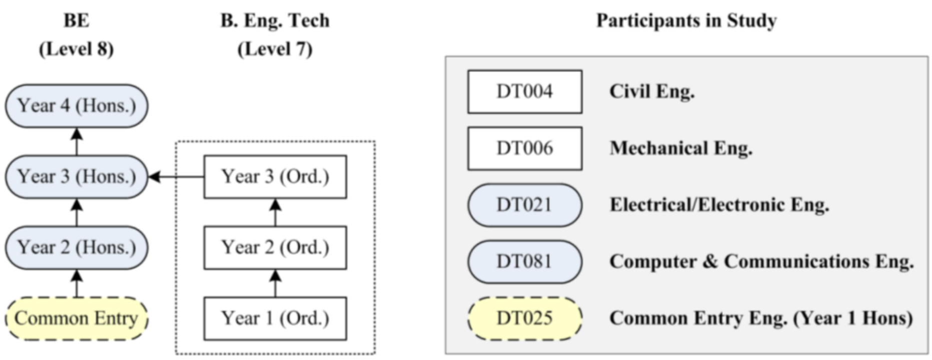

Fig. 3. Typical routes to Honours (Level 8) and Ordinary (Level 8) Engineering Programmes in DIT.

2 RESEARCH METHODS AND ANALYSIS

2.1 Current Study

Two tests of spatial cognition (the PSVT:R and MCT) were administered during regular class times for various programmes at DIT during semester 1 of the 2013-14 academic year. Students were given 20 minutes to complete each test. In a few cases, both tests were administered on the same day; however, in most cases the tests were administered approximately one week apart. Thus, for several students, scores are not available for both tests. At the end of the semester, student grades in their courses were obtained on a numerical scale of 0-100. For students on the Level 7 Civil Engineering programme the tests were administered during the second week of semester 2. It should be noted that in Ireland, a score of 40% is the minimum in order to receive a passing grade in most courses.

2.2 Participants

The students who participated in this study were drawn from first year Level 7 programmes in Civil (DT004) and Mechanical (DT006) engineering and Level 8 programmes in Electrical/Electronic (DT021) Engineering, Computer and Communications Engineering (DT081) as well as the Level 8 Common First year engineering programme (DT025).

2.3 Statistical Analysis

Two types of statistical analysis were utilised in this study. Correlation analysis was performed between results from the spatial skills testing and performance in courses. Figure 4 shows a typical graph from this analysis. Through this analysis, a correlation coefficient (r) is obtained which ranges between -1 and 1; the larger the absolute value of r, the better the correlation. Further analysis will demonstrate whether or not the correlation coefficient is statistically significant i.e. the probability that an effect is due to chance alone. In general, if $p < 0.05$ the correlation is thought to be statistically significant. For the graph shown in Figure 4, $r = 0.6963$ and $p = 0.011886$, indicating that this is statistically significant.

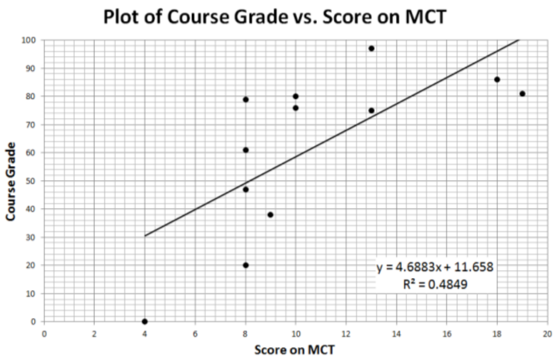

Fig. 4. Correlation between graphics course grade and score on MCT (n = 12).

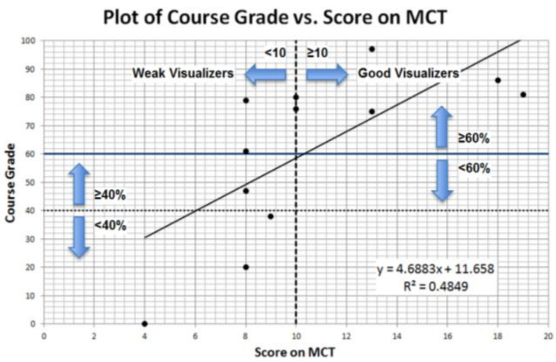

Fig. 5. Example scatter plot from for test of proportions (n = 12).

Examination of the correlation plots showed that in a large proportion of cases the data appeared to be quite scattered. An outlier represents a data point that deviates markedly from other points in the sample. The presence of outliers can adversely affect the value of the correlation coefficient and their removal can have a beneficial effect on correlation analysis [8]. An example of a potential outlier is illustrated in Figure 6. In this case the correlation coefficient is low ($r = 0.2703$, $p = 0.116174$). Removal of this single outlier significantly alters the correlation coefficient for the data ($r = 0.3866$, $p = 0.021784$).

To reduce the potentially significant impact of outliers, the second type of analysis performed in this study is a two-proportion z-test. For this analysis, each dataset was divided into four quadrants as illustrated in Figure 5 and 8. In previous studies conducted by Sorby et al [9], it was found that weak visualizers struggled more in learning CAD software. Based on this previous research, a cut-off of 21 out of 30 on the PSVT:R and 10 out of 25 on the MCT were estalished as the boundary between weak and strong visualizers. The vertical line in Figure 8 represents this cut-off on the MCT - students whose scores are to the right of this line are considered to be good visualizers; students whose scores are to the left are considered to be weak visualizers.

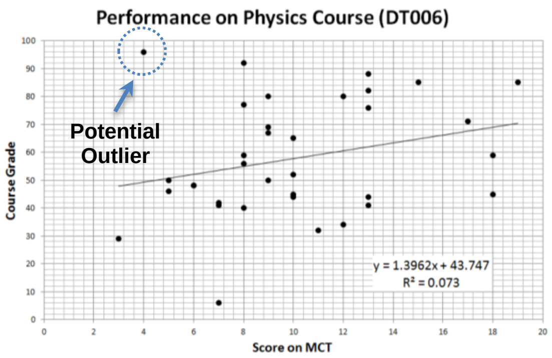

Fig. 6. Scatter plot with potential outlier indicated (n = 35).

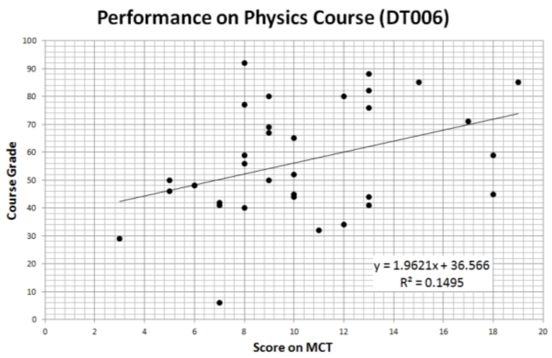

Fig. 7. Scatter plot with outlier removed (n = 35).

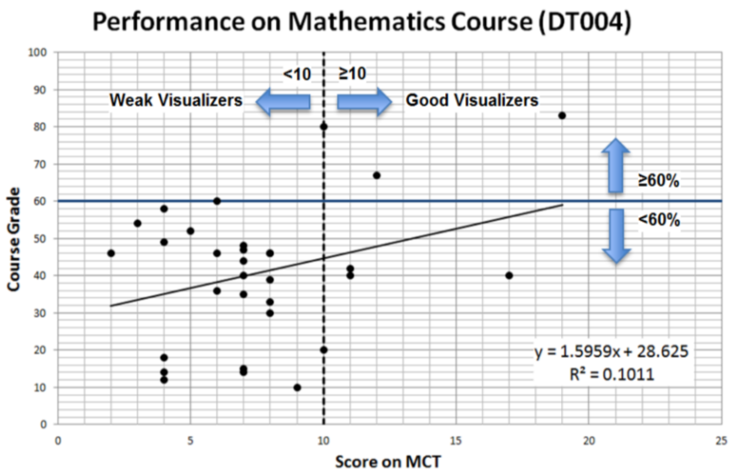

Fig. 8. Performance of DT004 students in mathematics based on MCT scores (n = 31).

In Ireland, a passing score in a course is 40%; however, 60% is considered to be "good progress" and is in many instances the minimum score required for further study in post-graduate programmes. The 60% pass mark is denoted by the horizontal line in Figure 8. Thus students who scored above this did well in the course and students who scored below did not do so well. A closer look at the data presented in Figure 8 shows that there were three good visualizers who did well in the course and four weak visualizers who did not do well; whereas, there was only one weak visualizer who did well in the course and 23 low visualizers who did poorly. Thus, for good visualizers, the proportion who did well was 42.9% and for poor visualizers the proportion was only was 4.3%. Statistical analysis shows that this difference is highly significant ($p = 0.0036$). For this study, the quadrants were created using the both 40% and 60% pass marks (see Figure 5).

3 RESULTS

The results presented in the following sections form part of an initial investigation looking into the relationship between spatial skills and selected core modules from the first year of a number of STEM related programmes. It should be noted that the results presented in this section are from a single semester. Programmes codes (see Figure 3) are used to identify the various student cohorts examined.

3.1 CAD/Engineering Graphics

Intuitively, it would seem that spatial skills are critical to success in engineering graphics due to the highly visual nature of the course. Links between high levels of spatial skills and performance in CAD/Engineering Graphics courses have been obtained in numerous previous studies [10] [11] [12].

For this analysis, graphics data was available only for the level 7 programmes in DT004 and DT006. Figure 8 illustrates available results for DT006. The graphics course on this program does not include a CAD component - assessments are based solely on hand drawing assignments. From the data presented, it is apparent that there is a strong correlation between a student's score on the MCT and their performance in the graphics course. The correlation between the graphics grade and MCT ($r = 0.6964$) is also statistically significant ($p = 0.0119$).

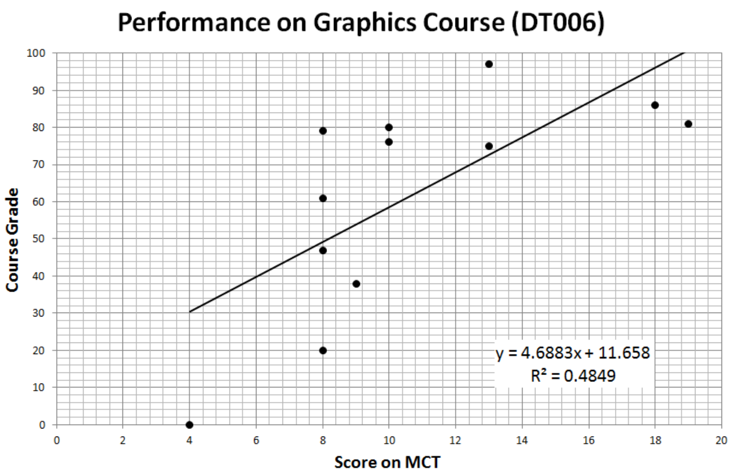

Fig. 8. Correlation between Graphics course grade and score on MCT (n = 12).

For DT004, significant correlations were not found between the score on the MCT and course grades. However, a significant difference in the proportion of students who scored well (≥60) in the course was found. For this analysis, 57.1% (4 out of 7) of the good visualisers scored well in their CAD/graphics course compared to only 20.8% (5 out of 24) of the weak visualisers. This difference in proportions was significant ($p = 0.0314$).

Table 1. Performance of DT004 students in CAD/Engineering Graphics based on MCT scores.

	Weak Visualizers	**Good Visualizers**
	score ≥ 40%	
Number	19	7
Total Number	24	7
Proportion	79.2%	100%
Significance	Not Sig. (p = 0.0934)	

	Weak Visualizers	**Good Visualizers**
	score ≥ 60%	
Number	5	4
Total Number	24	7
Proportion	20.8%	57.1%
Significance	Significant (p = 0.0314)	

3.2 Mathematics

Grades in mathematics courses were available for students on DT004, DT006 and DT025. No significant correlations were found for any of these courses; however, the proportion of students who scored higher than 40% and 60% in the courses was compared. The data based on MCT scores is presented in Table 2.

Differences for students other than those in the DT004 programme (score ≥60) were not significant. However, if we look at the proportion of students in DT006 who did not pass their initial mathematics course (i.e. scored less than 40% or did not complete the course), only 15% (3 out of 20) of the high visualizers were not successful compared to 33.3% (8 out of 24) of the low visualizers. This difference is not significant ($p = 0.081$); however, it is approaching significance.

Table 2. Performance of students in mathematics based on MCT scores.

	Civil Engineering (Level 7)		Mechanical Engineering (Level 7)		Common First Year Eng. (Level 8)	
	Weak Visualizers	**Good Visualizers**	**Weak Visualizers**	**Good Visualizers**	**Weak Visualizers**	**Good Visualizers**
Number (score ≥40%)	13	5	16	17	22	25
Total Number	24	7	21	20	31	40
Proportion	54.2%	71.4%	76.2%	85.0%	71.0%	62.5%
Significance	Not Sig. (p = 0.2090)		Not Sig. (p = 0.2389)		Not Sig. (p = 0.2266)	
Number (score ≥60%)	1	3	10	9	10	15
Total Number	24	7	21	20	31	40
Proportion	4.2%	42.9%	45.5%	45.0%	32.3%	37.5%
Significance	Significant (p = 0.0036)		Not Sig. (p = 0.4325)		Not Sig. (p = 0.3228)	

3.3 Physics

The only programmes for which Physics grades are available are DT006 and DT025. The results from the analysis for DT006 are presented in section 2.3 (see Figures 6 and 7). With the removal of the one apparent outlier, the correlation between physics performance and score on the MCT was statistically significant (p = 0.0165). For DT025, there was no significant correlation between spatial skills test score and overall grade in the course. Table 3 includes the physics grade data from this programme based on MCT test scores. Although the difference presented in this table is not statistically significant, it is approaching significance.

Table 3. Performance of DT025 students in Physics based on MCT scores.

	Weak Visualizers	Good Visualizers
	score ≥ 40%	
Number	22	26
Total Number	31	40
Proportion	71.0%	65.0%
Significance	Not Sig. (p = 0.2981)	

	Weak Visualizers	Good Visualizers
	score ≥ 60%	
Number	8	8
Total Number	31	40
Proportion	25.8%	20.0%
Significance	Not Sig. (p = 0.2810)	

3.4 Computer Programming

The only programme for which data is available for performance in a computer programming course was the DT021/081. Figures 9 and 10 show the scatter plots for course grades plotted against scores on the PSVT:R and MCT respectively. For this analysis, both correlation coefficients (r = 0.6505 for PSVT:R; r = 0.5639 for MCT) are highly statistically significant (p = 0.000075 for PSVT:R; p = 0.002697 for MCT). Table 4 outlines the performance of the students in computer programming based on their MCT scores. A possible reason for the high correlation may be down to the attraction of these types of courses to students who have a big interest in computer gaming [13].

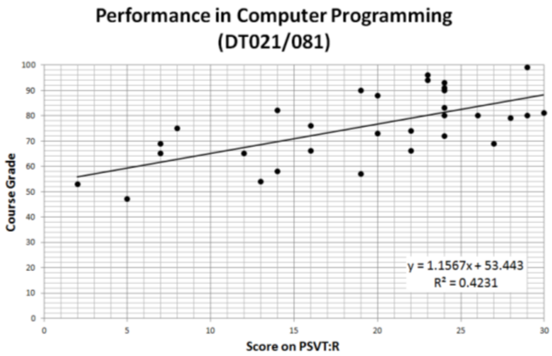

Fig. 9. Correlation between course grade and score on PSVT:R (n = 31).

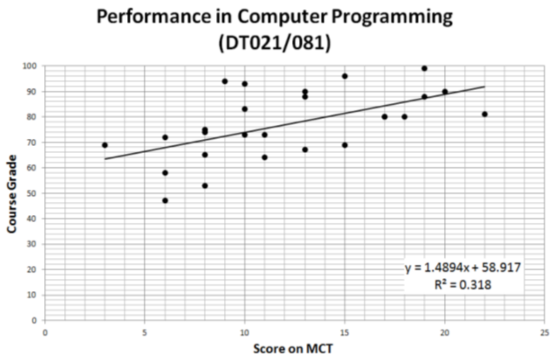

Fig. 10. Correlation between course grade and score on MCT (n = 26).

Table 4. Performance of DT021/81 students in Computer Programming based on MCT scores.

	Weak Visualizers	**Good Visualizers**
	score ≥ 40%	
Number	9	17
Total Number	9	17
Proportion	100%	100%
Significance	Significant (p = 0)	

	Weak Visualizers	**Good Visualizers**
	score ≥ 60%	
Number	6	17
Total Number	9	17
Proportion	67%	100%
Significance	Significant (p = 0.0057)	

4 SUMMARY AND CONCLUSIONS

Results from several modules of first year programmes in Civil, Mechanical, Electronic/Electrical and Computer and Communications Engineering were examined to measure the relationship between spatial skills and student performance.

The data obtained from this study would appear to show that the spatial skills of Irish students appear to be behind those of U.S. students who have taken part in similar studies [14]. In order to develop and enhance spatial skills as a means of improving student performance the identification of weak visualizers is key followed by appropriate intervention. This approach is supported by research elsewhere: Sorby [15] outlined where spatial skills were improved by providing special intervention classes; in a longitudinal study, Veurink and Sorby [16] presented results which demonstrated improvement in spatial skills, retention and attainment as a result of interventions.

The results presented in this study are limited in so far as they are drawn from a single semester. At this point it is too early to definitively say whether spatial skills will predict success or not among the cohort that participated. However, the incentive exists to continue this as part of a long-term longitudinal study which will track these students in order to determine long-term outcomes for weak and good visualizers. Subsequent results and findings may be used to direct and shape the ongoing development of current and future STEM related courses. In this context, the introduction of teaching interventions to improve spatial skills may contribute positively to student’s relative performance by improving results and contributing to long term student retention rates.

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