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The Effects of Spatial Skills and Spatial Skills Training on Academic Performance in STEM Education

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The effects of spatial skills and spatial skills training on academic performance in STEM education

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***Abstract**: Spatial ability plays an important but often unacknowledged role in achieving success in science, technology, engineering and mathematical (STEM) education. Many entering STEM disciplines have low spatial skills but these can be improved through a short training course. Accompanying improvements in academic grades and retention rates have been observed by others. This presents an opportunity to enhance the first year experience (FYE) for those with poor spatial skills. In this study the spatial skills of students entering several first year programmes in science and engineering were measured. Those identified as weak visualisers were offered a spatial skills course. Spatial skill post testing data were collected and correlations between academic grades and spatial ability were determined. No significant difference was found in the post test spatial scores of weak visualisers who attended and did not attend the course, nor was a significant difference found between the academic grades of weak and strong visualisers at the end of the first semester.*

Introduction

A student's experience of the first year (FYE) in college is particularly poignant in that it marks the start of a new journey in education, likely to lead to a professional career. It is a time of personal growth and development with many living away from home for the first time. In summarising a review of the FYE in the UK context, Yorke & Longden (2008) concluded that “*the first year has, to date, been the most critical for discontinuation*”. Likewise, in the US, retaining students during the freshman year is a critical challenge (e.g. Hartman & Hartman, 2006). Student retention has become a challenge in many institutes and persistence by a student in a programme he or she is not fully satisfied with should not be assumed. An extensive literature review by Harvey, Drew, & Smith (2006) highlighted a wide range of issues that affect student persistence ranging from extracurricular and social aspects of students' lives to what happens in the class room. Although what happens outside the classroom is the determining factor for some, many students leave programmes due to academic issues. In Yorke & Longden's (2008) study, 8 of the 19 students who left engineering selected 'insufficient academic progress' as influential in their decision to leave.

Many institutes now offer academic support to first years to assist them through the first year of their education. Such support typically attempts to address knowledge gaps that prevent students from engaging with new material. As explained by Ausubel (1968): “*If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly*”. In the engineering context, maths is often the subject selected for support with extra tuition offered to engineering students before they start college and/or during the academic year. Since many engineering subjects require prior knowledge in maths it makes sense to provide students the opportunity to bridge gaps in prior knowledge so they can engage more fully with the curriculum and avoid slipping behind.

Mathematical and verbal ability are typically selected as academic indicators of success in STEM education research (e.g. French, Immekus, & Oakes, 2005; Guili, Anderson, Ohland, & Thorndyke, 2004) as these are considered to express a student's academic ability sufficiently well. However, as explained by Wai, Lubinski, & Benbow (2009), models that predict success in STEM education can be significantly improved by including spatial ability. In many cases, students without high maths and verbal abilities but with high levels of spatial skills have achieved high levels of success in STEM education. In their study using a large dataset ($n \approx 400,000$), the vast majority of STEM graduates at Bachelors, Masters and PhD level came from the group with highly developed spatial skills at age 13. In addition to mathematical and verbal skills, the inclusion of spatial ability as a key cognitive attribute was recommended by a recent report on facilitating innovation in the STEM area (National Science Board, 2010).

In the context of engineering education at Michigan Technological University (MTU), several studies over the last two decades have shown that students cannot be assumed to have good spatial skills when they arrive at university, female students are likely to have lower spatial skills than males and that spatial skills can be improved with relatively little effort and lasting results (Sorby, Casey, Veurink, & Dulaney, 2013; Veurink & Sorby, 2011). Sorby & Baartmans (2000) found that 18 % of a group of first year engineering students failed a spatial skills test administered on entry to college. When support was provided to a sample of this group in the form of a short spatial skills course, grades in engineering graphics, computer science, calculus and chemistry improved by as much as 10 %. Retention rates were 12 % higher for those who took the course compared to those who didn't (59 % v 47 %). These data were collected when enrolment on the course was voluntary thereby introducing the possibility that other factors, such as overall motivation to succeed, might be a mitigating factor and that Veurink & Sorby (2011) attributed the improvement to the spatial skills course in error. However, when the course became compulsory for those who failed, benefits were still observed. The retention rates of this group were higher than those who marginally passed the test (83 % v 80 %) and likewise for grades (2.83 v 2.64 GPA) (Veurink & Sorby, 2011). Another interesting finding from this work was that women who take the course were retained at much higher rates than their male counterparts. Spatial skills should not be taken for granted but can be improved and, like maths, influence an engineering student's ability to perform well in general and persist with the programme.

Every educational context has its own unique properties so it is important to not only understand what others have studied in different locations but to also know as much as possible about what is going on in one's own institution. In the words of Pitkethly & Prosser (2001), "*each university must understand the experiences of its own students, if it is to address attrition*". In addition, spatial ability also has a context dependency as ability levels in the general population vary by country (Lippa, Collaer, & Peters, 2010) and socio-economic status (Wai, et al., 2009). At our institute 55 % of first year students on three year technology programmes progress to the second year while 70 % of first year students on four year engineering programmes make it into second year. While many factors influence progression, the results from MTU provided the motivation for this study. Consequently we felt that an investigation into the spatial skills levels of students entering STEM programmes was worth conducting and the benefits of spatial skills training for those identified as weak visualisers should be evaluated. The objectives of this study were to measure spatial skills levels at the start of the year, compare these to international data, analyse them by gender and nationality, categorise students based on spatial skill level, deliver a short course on spatial skills to those labelled as weak in this area, measure spatial skills again at the end of the semester and compare these to semester 1 grades.

Research Design

This study was conducted at Dublin Institute of Technology (DIT) during the academic year 2014/15. DIT offers three year Bachelor of Technology programmes in addition to the standard Bachelor of Engineering, Bachelor of Science, etc. Compared to the B. Tech. programmes, the BE/BSc programmes have higher academic entry requirements and require an extra year of tuition (240 v 180 ECTS). In order to have as broad a sample of STEM students as possible it was decided to include first year students in both B. Tech. and BE/BSc programmes in engineering, built environment and science.

Table 1. List of programmes with students who were offered a spatial skills course

Programme Code	Title	College	Academic level[a]	Class size	Weak visualiser	Attended course[b]
DT222	Physics Technology	Science	8	9	1	4 (1)
DT227	Science with Nanotechnology	Science	8	26	7	10 (1)
DT235	Physics with Medical Physics & Bioengineering	Science	8	14	6	6 (1)
DT004	Civil Engineering	Engineering	7	40	18	21 (2)
DT066	Engineering, common entry	Engineering	8	167	34	20 (3)
DT097	Engineering, common entry	Engineering	7	40	14	6 (4)

[a] Level defined by Irish National Framework of Qualifications (Quality and Qualifications Ireland, 2014); level 7 is a 3 year programme leading to a Bachelor of Technology, level 8 is a 4 year programme leading to a Bachelor of Science or Engineering.

[b] The course was run at four different times in the week. This column shows the number who attended and the course they attended in brackets.

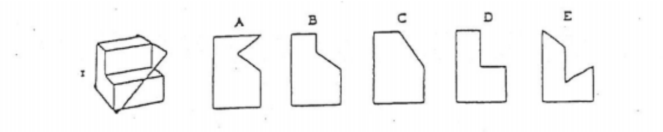
Participants

The majority of first year students enrolled in STEM courses across 25 different programmes were administered two spatial skills tests at separate times in the first two weeks of the first semester (September 2014) - the Mental Cutting Test (MCT, CEEB, 1939) and the Purdue Spatial Visualisation Test: Rotations (PSVT:R, Guay, 1976). The response rate was highest for the MCT pre test (n = 913) as it was administered during the induction week when students from several programmes were gathered together at the same time while the PSVT:R pre tests (n = 627) were administered in class during normal timetabled hours and relied on the cooperation of academic staff. Those scoring less than 60 % on the PSVT:R were categorised as weak visualisers and deemed eligible to enrol in the spatial skills intervention course. This mark was chosen to allow us to compare results with MTU data. For practical reasons related to workload and timetables, the intervention was offered to eligible students from only 6 of the first year science and engineering programmes in semester 1. A summary of sample sizes is shown in Table 1. At the time of writing retention data was not available and we were unable to explore the relationship between spatial skill development and retention rate.

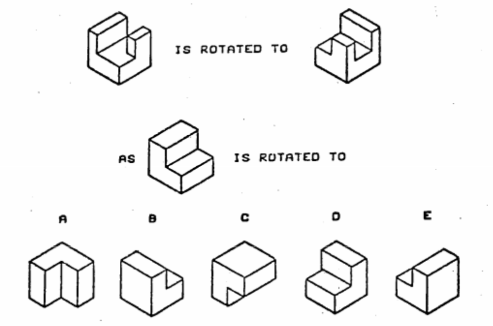
Spatial skills course

The spatial skills intervention course was developed by Sorby & colleagues (Sorby, 2009; Sorby & Baartmans, 2000) and contains 10 sections covering several technical graphics procedures that require spatial thinking. It is delivered using computer based training and a workbook with paper and pencil activities. Several challenges were faced in delivering the course: a learning curve for tutors associated with delivering it for the first time, access to students with a busy timetable, student motivation to attend an extra-curricular activity as manifested in sporadic attendance by some, and a delayed start with a rushed delivery. Of the n = 80 students eligible to take the course n = 43 attended two or more of the 6 x two hour sessions that comprised the total course delivery time. An additional n = 18 students opted to do the course who had either missed the pre test or achieved a mark higher than 60 %. The PSVT:R was administered a second time in the first week of semester 2 as a post-test but only to students on the 6 programmes included in the spatial skills course in semester 1. All students in these classes were asked to complete the post-test regardless of whether they had attended the course or not. The MCT was also administered as a post test but only to the science classes. Due to variability in student attendance, the number of respondents to each test varies.

Although the course is normally delivered over 10 x 90 minute sessions, due to a delayed start, it was delivered over 6 weeks with a 2 hour session each week. It was scheduled at four different times in the week to accommodate students from 6 different programmes. For one programme, DT004, it was integrated into the class time but for the others it was an extracurricular activity. Although different instructors delivered each of the four sessions, all had received the same training, used the same software, followed the same lesson plan and met once a week to compare notes on progress. One group, DT066, did not attend the last session (no. 6).



(a)



(b)

Figure 1. A sample question from (a) the MCT (CEEB, 1939) and (b) the PSVT:R (Guay, 1976)

Spatial Tests

The MCT consists of 25 multiple choice questions with one correct answer and four distracters and is primarily a test of spatial visualisation and mental transformation. A simple sketch of a three-dimensional (3D) object is shown with a plane slicing through it. The participant must visualise the shape of the face cut by the plane and select an answer. It is an individual test with a time limit of 20 minutes.

Mental rotation ability was assessed using the PSVT:R which is similar in format to the MCT. It contains 30 multiple choice questions. Each question contains an example of a simply sketched 3D object shown in original and rotated positions. Below is another 3D object and participants are asked to visualise what this object would look like if subjected to the same rotation as the example and pick an answer from five options. Again, there is one correct answer and four distracters. 20 minutes are allowed and participants work alone. For both tests, those finishing early were asked to check their answers and remain quietly seated until the test is finished.

Results

The results from all four spatial tests are provided in Table 2 for the all first year students, for students on the 6 programmes included in the spatial skills course both for each programme and for all 6 programmes combined.

Table 2: Sample sizes, means and standard deviations for all spatial test results.

	MCT Pre			MCT Post			PSVT:R Pre			PSVT:R Post		
Programme Code	n	M	SD	n	M	SD	n	M	SD	n	M	SD
All 1st Years	913	9.53	4.74				627	18.20	7.28			
DT004	36	10.22	5.21				38	17.11	6.45	31	20.55	4.97
DT066	133	11.83	4.86				142	21.35	6.29	106	23.37	5.50
DT097	43	10.77	4.31				40	20.22	5.61	41	20.66	5.54
DT222	9	12.22	3.87	9	15.78	3.38	9	24.56	3.97	9	26.22	4.09
DT227	25	9.80	4.02	18	12.28	4.39	25	20.88	6.04	19	22.26	6.55
DT235	16	10.56	5.83	14	12.57	6.51	14	20.36	7.31	14	21.43	6.90
Above 6	262	11.18	4.81	41	13.15	5.13	268	20.59	6.34	148	23.22	5.74

Correlation between spatial tests and academic grades

A series of bivariate correlation tests, using a Pearson correlation with cases excluded pairwise and bias-corrected and accelerated bootstrapping, were conducted to examine the relationships between each of the spatial tests and semester 1 academic results. While the curriculum varies with each programme, a semester 1 average grade and a maths grade were available for all and these academic results were included in the correlations with the spatial test scores. Separate tables are provided for science (Table 3) and engineeringTable 4) as different correlation patterns were observed for each.

Table 3. Correlation results for spatial tests and academic grades of science students

	Maths[a]				Sem1 Average[a]			
	r	p	Lower	Upper	r	p	Lower	Upper
MCT Pre test	.436**	.007	.102	.746	.488**	.002	.195	.756
MCT Post test	.500**	.002	.226	.775	.494**	.002	.248	.722
PSVT:R Pre test	.239	.154	-.023	.490	.237	.158	-.008	.478
PSVT:R Post test	.307	.064	.024	.533	.330*	.046	.081	.554

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
[a] n = 37

Table 4. Correlation results for spatial tests and academic grades of engineering students

	Maths[a]				Sem1 Average[a]			
	r	p	Lower	Upper	r	p	Lower	Upper
MCT Pre test	-.264*	.024	-.490	-.032	-.108	.364	-.380	.154
PSVT:R Pre test	-.118	.320	-.378	.136	-.101	.395	-.338	.136
PSVT:R Post test	-.047	.693	-.246	.170	.072	.545	-.157	.305

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
[a] n = 73

The samples were then divided based on spatial skill level as measured by the PSVT:R Pre test and categorised as follows:

Table 5. Categorisation based on PSVT:R pre test score

PSVT:R Score	Category
< 18	Weak visualiser
18 ≤ Score ≤ 20	Marginally above threshold
> 20	Strong visualiser

When the mean values for Maths and the Semester 1 Average grades were calculated separately for weak and strong visualisers and then compared using an independent samples t-test no significant differences were found.

Analysis by gender

The entire first year sample was divided based on gender and descriptive statistics for each test were then determined as shown in Table 6.

Table 6. Descriptive statistics based on gender for spatial tests and results from comparing means with an independent samples t-test and Cohen's d effect size

	Male			Female					
	n	M	SD	n	M	SD	t	p	d[a]
MCT Pre test	564	9.48	4.62	122	8.33	4.64	2.51*	.012	0.25
MCT Post test	30	13.90	5.05	13	10.85	4.58	1.869	.069	0.63
PSVT:R Pre test	246	18.77	7.22	89	15.26	8.20	3.79**	.000	0.45
PSVT:R Post test	53	23.23	5.27	16	19.81	6.71	2.13*	.037	0.57

** Difference in means is significant at the 0.01 level (2-tailed).
* Difference in means is significant at the 0.05 level (2-tailed).
[a] Cohen's d effect size = $(M_2-M_1)/\sqrt{(SD_1^2+SD_2^2)/2}$

Effect of intervention on spatial skills

Table 7. Comparison of PSVT:R pre and post test results based on spatial skill level and attendance at the spatial skills course

		PSVT:R Pre Test		PSVT:R Post Test				
	n	M	SD	M	SD	t	p	d[a]
Weak, Did Attend	39	12.90	3.77	17.74	5.67	5.94	.000**	1.01
Weak, Did Not Attend	29	13.07	3.54	17.31	6.12	4.05	.000**	0.85
Marginal	23	19.22	0.85	21.74	2.58	4.46	.000**	1.31
Strong	109	25.41	2.66	25.89	3.31	1.71	.091	0.16

** Difference in means is significant at the 0.01 level (2-tailed).
[a] Cohen's d effect size = $(M_2-M_1)/\sqrt{(SD_1^2+SD_2^2)/2}$

When the data in Table 7 were divided by gender the sizes of the female samples were very small (n < 10) so it was decided not to pursue any statistical analysis with regard to gender. Hence, the same correlations were not checked for males and females separately.

Discussion

As shown in Table 7, the spatial skills of all groups improved during the semester. This improvement was significant at the p < .001 level for weak visualisers regardless of whether they attended the course or not. A total of 4 of the 23 marginal visualisers indicated in Table 7 attended the spatial skills course. When these 4 were removed the PSVT:R post test score dropped only slightly and the paired samples t-test was still significant (t = 3.65, p = .002). Those who were strong visualisers achieved a higher post test score but this lacked significance. This group are close to the maximum score and have little room left to improve. If a normalised gain (actual improvement divided by maximum possible improvement) was computed the result would be more favourable for this group. Either way, their spatial skills, as measured by the PSVT:R are very good and they should probably devote attention to improving other skills.

When compared to data reported by Sorby et al. (2013) and Sorby & Baartmans (2000) the gains made by the students in this study identified as weak visualisers are lower for both PSVT:R pre and post tests. Where US students progress from approximately 50 to 80 % on the pre and post tests by participating in the intervention, students in this study had equivalent scores of approximately 43 and 60 %. Given the years of experience running this course at MTU it is very likely that our delivery – rushed, poorly attended by some and novice tutors – was of a poorer quality. In addition, the average PSVT:R pre test score for the entire sample (all visualisation levels, both genders) is reported as 23.97 (80 %) by Sorby et al. (2013) whereas we computed an average of 18.20 (61 %) for our first year students. Likewise, comparisons with results of spatial tests from an institute in Poland and another in Germany show the DIT students achieving lower scores than their European counterparts (Sorby, Leopold, & Gorska, 1999). We have refrained in this paper from speculating about reasons for this difference. Returning to the conclusions provided by Wai et al. (2009), this implies our students are less likely to succeed in STEM education than their counterparts in other countries.

It was interesting to find that weak and marginal visualisers significantly improved spatial skills regardless of whether or not they attended the course. It was encouraging, though, to see many students improve their spatial skills simply by attending their courses of study. Does this mean an extracurricular spatial skills course is not needed in this context? Is there some aspect of the curricula these students experience that helps develop spatial ability? Both the Common Engineering (DT066) and Civil Engineering (DT004) curricula contain a 5 credit module (approx. 100 hours of learning) on technical graphics in semester 1 that includes freehand sketching and computer drawing software whereas the Science students do not take such a module. The PSVT:R Pre and Post test data were separated for each of these groups (Table 8) to check if they had all made similar progress. While all three groups improved, the improvement for the science group was not significant. However, there was a significant difference in the means of the MCT post test scores for the science students categorised as weak visualisers (7.25 v 10.17, p = .007, n = 12).

Table 8. Comparison of PSVT:R pre and post test results for different programmes

		PSVT:R Pre Test		PSVT:R Post Test				
	n	M	SD	M	SD	t	p	d^a
Science	13	14.15	3.91	15.85	5.08	1.59	.138	0.38
DT004	16	11.56	3.63	17.31	3.96	6.66	.000**	1.51
DT066	10	13.40	3.44	20.90	7.67	3.48	.007**	1.26

** Difference in means is significant at the 0.01 level (2-tailed).
[a] Cohen's d effect size = $(M_2-M_1)/\sqrt{(SD_1^2+SD_2^2)/2}$

The lack of significant improvement by the science students who took the course and lack of a significant difference between the PSVT:R post test scores of weak visualisers who attended and didn't attend, as shown in Table 7, casts doubt on the effectiveness of the spatial skills course we delivered. Compelling evidence to show the benefits of attending the course in terms of higher PSVT:R scores did not emerge. Sample sizes are very small ($n \leq 16$) and we consider it advisable to collect more data before settling on conclusions. However, it raises the possibility that spatial skill development could be attributed mostly to the technical graphics modules rather than the course in this case. It may be that 6 x two hour sessions are not sufficient to facilitate significant development in our context. The relatively low PSVT:R scores of our students indicates they have more work to do to reach the 80 % post test level achieved by their US peers. A longer, rather than shorter, spatial skills course might be necessary in our context.

The findings with regard to the correlation between spatial ability and academic ability, as defined by grades in a maths module and a semester 1 average grade were inconclusive (Table 3 and Table 4). Firstly, a significant and large correlation between MCT and maths was observed for the science students but this was not supported by the PSVT:R scores. Secondly, for the engineering students the only significant correlation between maths and spatial ability was for the MCT and it was negative. Where significant correlations between spatial ability and maths have been reported they relate to courses focused on calculus (Sorby, et al., 2013), geometry and problem solving (Casey, Nuttall, & Pezaris, 2001). The semester 1 maths module in DT066 is not a calculus module but covers vectors, functions, matrices and complex numbers. Calculus is covered in semester 2 and the correlation of grades in that module with spatial skills will be investigated. In short, the academic gains promised for weak visualisers by doing the course were not observed in this study nor did we find that strong visualisers achieved significantly higher academic grades. Therefore, even if we ran an effective spatial skills course and brought students to the 80 % level on the PSVT:R we are not likely to their grades improve at the end of semester 1. However, we do not suggest that our relatively small study over one semester is sufficient to counter the findings from approximately 20 years of research at MTU (Sorby & Veurink, 2010).

Conclusions

Students entering first year programmes in engineering and science at DIT have lower spatial skills as assessed by the PSVT:R and MCT than their peers in the US and Europe. An established spatial skills course that has been shown to significantly improve spatial skills elsewhere was delivered in a relatively short time as part of this study and was not found to improve spatial skills. If we are to facilitate spatial skill development to levels similar to US students a longer version of the course we trialled in this study might be needed, possibly spanning two semesters. Also, an alternative to the extracurricular mode of delivery should be found in order to remove the difficulties students had in attending all the lessons. Grades in semester 1 assessments for many first year courses examined in this study do not correlate with spatial skill level. Further work is needed to collect academic and retention data over a longer time period for these students in order to examine how spatial skills correlate with performance beyond the first semester.

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