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A Profile of the Spatial Visualisation Abilities of First Year Engineering and Science Students

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***Abstract**: The link between spatial visualisation skills and academic and professional achievement in STEM fields is well established. It is also widely documented that men outperform women on tests of spatial ability. This disparity puts women at a relative disadvantage for academic success in STEM disciplines. Our research explores the influence of secondary academic experience on spatial visualisation ability among first year students entering an engineering or science programme. Spatial ability was measured using two standard psychometric instruments for measurement of spatial visualization. Out of eight secondary courses considered, a single course in design and computer graphics emerged as a predictor of spatial ability. Students who took this course had significantly higher scores on both measures of spatial cognition than students who did not take the course. There was no significant difference in test scores of men and women who took the course. A significant gender gap was observed among students who did not take the course.*

Context

Spatial skills are the ability to understand and remember the spatial relationships among objects. Linn and Petersen (1985) describe three categories of spatial skills based on the processes used in solving spatial tasks:

1. Spatial perception requires the understanding of spatial relationships with respect to a reference orientation.
2. Mental rotation is the ability to rotate a two or three-dimensional figure rapidly and accurately.
3. Spatial visualization is associated with tasks that involve complicated, multistep manipulations of spatial information.

A well-established link exists between spatial skills and academic and professional success in STEM fields (Humphreys, Lubinski, & Yao, 1993; Shea, Lubinski, & Benbow, 2001; Sorby, 2009; Wai, Lubinski, & Benbow, 2009; Wai, Lubinski, Benbow, & Steiger, 2010). A longitudinal study of 400,000 high school students tracked eleven years after graduation exemplified how tests of spatial ability are useful in predicting group membership in various engineering and physical science occupations (Humphreys et al., 1993). Research conducted at Michigan Technological University in the United States showed that spatial skills were a strong predictor of academic achievement and retention in engineering (Sorby, 2009). Among the significant implications of these findings are (1) failure to consider spatial skills in the college selection process can result in a loss of potential talent (Humphreys et al., 1993; Johnson & Bouchard, 2005) and (2) supporting the development of spatial skills can increase the academic success of students in engineering (Sorby, 2009).

Gender differences in spatial ability, favouring men, are widely reported in the literature (Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000; Debelak, Gettler, & Arendasy, 2014; Halpern et al., 2007; Maeda & Yoon, 2013; Voyer, Voyer, & Bryden, 1995). The differences are mainly limited to mental rotation ability (Linn & Petersen, 1985; Voyer et al., 1995), which is also the ability most predictive of success in engineering and physical sciences (Guay, 1976; Johnson & Bouchard, 2005; Kozhevnikov, Kozhevnikov, Chen, & Blazhenkova, 2013). Sorby and co-authors (Sorby, 1999, 2001, 2009) reason that poorly developed 3-D spatial skills of women may be a hindrance, especially to women, to success in engineering programs. The removal of such barriers to academic success is of particular interest in the context of current efforts to increase the number of engineering graduates entering the workforce and to increase the participation of women in the profession.

Despite the disparate spatial abilities of beginning college engineering and science students, fortunately, there is evidence that spatial skills can be improved in a relatively short time through appropriate instruction. Targeted spatial skills interventions have resulted in substantial gains in spatial skills test scores, eliminate the gender gap in spatial skills test scores, improved student academic performance in engineering courses, and increased retention of students at the university (Hsi, Linn, & Bell, 1997; Sorby, 2009).

A variety of test instruments are used to measure spatial ability. Tests of three-dimensional spatial ability are of particular interest in engineering education and have been most widely used in educational and psychological research related to STEM fields.

- The Mental Cutting Test (MCT) (CEEB, 1939) is a twenty-minute timed test comprising 25 items. This test measures both spatial relations and spatial visualization ability.
- The Purdue Spatial Visualization Test: Rotations (PVST:R) (Guay, 1976) is a 30-item test. Each question presents the subject with a depiction of a 3-dimensional reference object and a picture of the object after it has been rotated about one or more axes. A picture of a second object is shown, and the subject must indicate which of five choices depict the object after it has undergone the same rotation as the first object. This test requires a higher level of spatial visualization ability than other tests by maximizing gestalt-type processing and minimizing analytical processing. Gestalt processing is related to the ability to solve tasks often found in STEM disciplines (Bodner & Guay, 1997).
- Differential Aptitude Test: Spatial Relations (DAT:SR) (Bennett, Seashore, & Wesman, 1973) comprises 50 questions. The learner must mentally fold a two-dimensional pattern

and identify the resulting three-dimensional object. The test measures the learner's ability to move from a two-dimensional space to a three-dimensional space.

- The Mental Rotations Test (MRT) (Vandenberg & Kuse, 1978) consists of 20 questions that ask the learner to compare two-dimensional drawings and three-dimensional geometric figures. The test is timed; there are two sections of four minutes each with a short break between sections. A reference figure is presented, and the subject must choose two pictures (among four choices) that correctly represent the object after it is rotated. This test is simpler than the PSVT:R due to the use of cubic surfaces in the test questions, rather than inclined, oblique and curved surfaces (Yue, 2004).

Questions of recruitment and selection of STEM students has been the subject of numerous research studies. For example, the research study by Humphreys et al. (1993) demonstrates that potential STEM talent is lost by restricting assessment to conventional abilities, and the authors recommend a space-math composite college admissions criterion because it is a stronger predictor of success in STEM professions. Entry to higher education in Ireland is awarded on a points system based solely on the Irish Leaving Certificate examination, which is taken in the final year of study at second level.

Due to the high stakes of the Leaving Certificate examination, students strategically select approximately 7-9 courses of study during their last two years of study in second level education. Irish, English, mathematics and a foreign language are mandatory. According to the points system, the candidate's best six examination subject marks are considered in the total Leaving Certificate score. The maximum points possible to achieve in the examination is 600 points. The marking scheme for the leaving certificate is shown in Table 1.

Table 1. Leaving Certification points based on grade for higher and ordinary level exams. CAO awards 25 bonus points to students who take the Higher Leaving Certificate Mathematics Paper.

Percentage	90-100	85-89.99	80-84.99	75-79.99	70-74.99	65-69.99	60-64.99	55-59.99	50-54.99	45-49.99	40-44.99	25-39.99	10-24.99	0-9.99
Grade	A1	A2	B1	B2	B3	C1	C2	C3	D1	D2	D3	E	F	NG
Higher	100	90	85	80	75	70	65	60	55	50	45			
Ordinary	60	50	45	40	35	30	25	20	15	10	5			

The Irish Central Applications Office is responsible for processing applications made to higher education institutions for placement in first year undergraduate courses. Students may indicate up to 10 ranked choices for level 8 studies and additional 10 ranked choices for level 6/7. Higher education institutions select applicants based on a points system which specifies a minimum requirement for total leaving certification points, and often a minimum points requirement for specific subjects relevant to the specific course applied for. Placement in a specific programme is offered to qualifying students in order of point ranking until the available places have been filled.

Research questions

This work explores the following research questions about the spatial skills of students entering a third-level engineering or physical science programme:

1. What is the relationship between secondary academic experience and spatial ability among students entering third level science and engineering programmes? Which secondary courses are the best predictors of performance on tests of spatial cognition?

2. Among students entering a third level science and engineering programme, is there a difference in spatial visualization ability based on gender? If so, is this difference mitigated through prior academic experience?

Theoretical and conceptual framework

This work is grounded in a constructivist, socio-cultural framework based on theories put forth by Piaget and Inhelder (1971) and Brunner (1977). The developmental psychologist Jean Piaget suggested that perception and mental imagery develop as life-long processes and can be learned throughout childhood and adulthood. Brunner socio-cultural theory highlights the importance of individual differences based on environmental influences and methods of representation used. This work is further guided by hierarchical models of cognition that include a factor of general intelligence and third-stratum elements such as verbal, perceptual and image-rotation, e.g., (Johnson & Bouchard, 2005).

This study is based on empirical evidence demonstrating that spatial skills can be learned into adulthood (Uttal et al., 2013) and are strongly linked with academic and professional success in STEM fields (Humphreys et al., 1993; Shea et al., 2001; Sorby, 2009; Wai et al., 2009; Wai et al., 2010) .

Methods

The sample group included all level 7 and level 8 students entering the College of Engineering and Built Environment and the School of Physics at Dublin Institute of Technology who were in their first year during the academic year 2014-2015. Level 7 is a three year ordinary degree programme leading to a BTech degree, and Level 8 is a four year honours degree programme leading to a BE degree. A student entering a Level 8 programme would generally have a higher level of mathematics preparation than a student entering a Level 7 programme.

Two tests of spatial cognition (MCT and PSVT:R) were administered at the beginning of the fall semester. The MCT was administered to all incoming students in the College of Engineering and Built Environment and the School of Physics during the required induction event in the first week of class. Almost 100 % of the students took the MCT. The PSVT:R was administered separately to students in various programs during regular class times within the first three weeks of class. The PVST:R was administered to 18 out of 26 programs, and participation was also dependent on class attendance. The tests were conducted with the time limits of 20 minutes for the MCT and 20 minutes for the PSVT:R.

CAO test results were obtained for all students in the sample group. Numerical scores were assigned to each CAO grade according to the scheme in Table 1. For students who completed Irish secondary education, their CAO test results in eight different subjects of interest were examined. The leaving certificate test subjects chosen were mathematics, applied mathematics, English, Design and Computer Graphics (DCG), Engineering, Chemistry, Physics, and Technology. Mathematics, physical sciences, and engineering/technology courses were chosen because they are thought to be most closely related to science and engineering in higher education. English was chosen as the closest measure of verbal ability, which, with spatial skills and mathematics is an important cognitive domain.

Results

General profile of first year students

A total of 904 students completed the MCT spatial skills pre-test, and 627 students who completed the PSVT:R pre-test.

For the MCT and PSVT pre-tests and Mathematics CAO tests, correlations were examined between those tests and the eight CAO testing subjects considered in this study. Table 2 provides descriptive statistics for each test. The mean test scores for the MCT pre-test, PSVT pre-test, and eight selected CAO test scores are shown in Table 2. The mean score on the MCT pre-test was 38.22%, and the mean score on the PSVT:R pre-test was 60.65%. This is consistent with previous findings indicating that the MCT is the more difficult test

(Sorby, Leopold, & Gorska, 1999). Table 3 shows the correlation results for each test with the MCT, PSVT:R and mathematics leaving certification. The scatter plots for the three correlations that will be examined more closely, MCT-PSVT:R, MCT-DCG and PSVT:R-DCG, are shown in Figure 1. Not surprisingly the MCT and the PSVT:R spatial skills test scores were found to be significantly related (r=0.646, p<0.01, n=532, 2-tailed). This correlation between different measures of spatial intelligence is slightly stronger than that found by Sorby (2000). The next strongest correlation is found between each of the spatial skills tests and the DCG test. The correlation between the MCT and the DCG is (r=0.516, p<0.01, n=216, 2-tailed), and the correlation between the PSVT and the DCG is (r=0.410, p<0.01, n=112, 2-tailed). Thus, among the leaving certificate subjects, the DCG test is the strongest predictor of high scores on the two spatial skills tests given.

Our findings that there are moderately strong correlations between secondary school academic experiences and measures of spatial ability differ significantly from the findings of Deno (1995) who found non-academic high school experiences to be the best predictor for spatial skill measurement in first year college engineering students (r=0.12, p<0.01). It should be noted that Deno (1995) used the MRT instead of the PSVT:R and MCT.

Table 2. Descriptive statistics for spatial skills tests and leaving certificate tests for students in the College of Engineering and Built Environment and the School of Physics at DIT

	MCT (%)	PSVT (%)	CAO MATHS	CAO GTD	CAO ENR	CAO CHM	CAO Phys	CAO TEC	CAO AMT	CAO ENGL
Mean	38.22	60.65	50.01	69.87	75.11	50.24	54.59	73.00	55.71	55.31
sd	18.947	24.273	28.554	15.334	13.138	18.275	15.034	11.697	14.559	17.791
N	904	627	759	223	189	106	229	45	35	765

Table 3. Partial correlation matrix showing the correlation for the MCT, PSVT and CAO mathematics with all tests.

		MCT	PSVT	CAO MATHS	CAO DCG	CAO ENR	CAO CHM	CAO Phys	CAO TEC	CAO AMT	CAO ENGL
MCT	Pearson Correlation	1	.646**	.370**	.516**	.314**	.084	.187**	.317*	.318	.102**
	Sig. (2-tailed)		.000	.000	.000	.000	.402	.006	.041	.081	.006
	N	904	532	716	216	177	102	216	42	31	720
PSVT	Pearson Correlation	.646**	1	.364**	.410**	.326**	-.035	.087	.143	.087	.100*
	Sig. (2-tailed)	.000		.000	.000	.001	.760	.284	.515	.680	.032
	N	532	627	454	112	110	78	152	23	25	460
CAO MATHS	Pearson Correlation	.370**	.364**	1	.537**	.549**	.447**	.670**	.460**	.729**	.294**
	Sig. (2-tailed)	.000	.000		.000	.000	.000	.000	.002	.000	.000
	N	716	454	759	218	184	105	227	44	34	746

None of the other correlations between spatial skills test results and leaving certificate test results were associated above the r=0.4 level; the next-best predictor of spatial skills measurement was the mathematics leaving certificate. The MCT scores and mathematics leaving certificate scores correlated positively (r=0.370, p<0.01, n=716, 2-tailed). The PSVT:R test score also correlated positively with the mathematics leaving certificate test (r=0.364, p<0.01, n=454, 2-tailed).

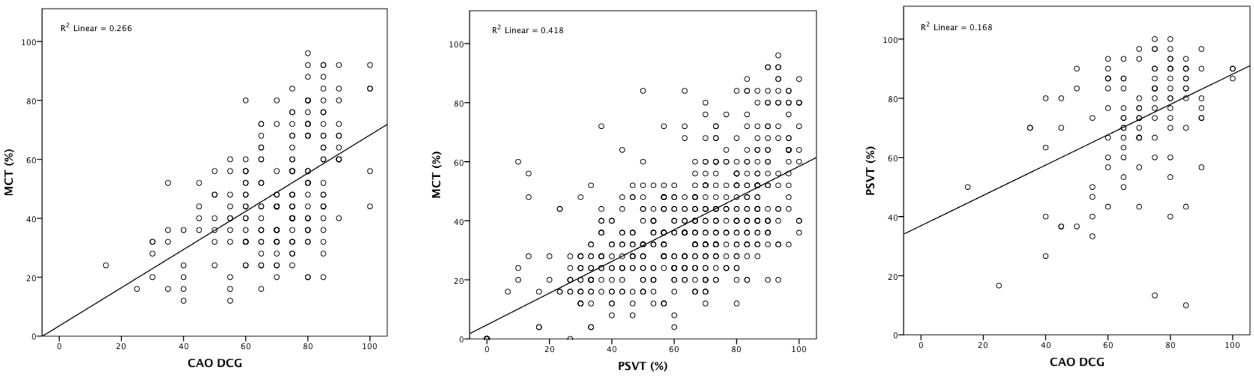

Figure 1. Correlation scatter plots for the three correlations of interest.

Gender Differences

For both of the spatial skills tests, there is a significant difference in performance based on gender, with males outperforming females. The means and standard deviations are presented in Table 4. The one-way analysis of variance revealed significant differences in spatial skills between males and females: for the MCT, F(1, 876)=11.231, p=0.001; for PSVT:R, F(1,567)=21.064, p<0.001.

In contrast, the female students outperform the male students on every one of the eight CAO test subjects, with significant differences (p<0.01) for mathematics, physics, and English.

Table 4. Spatial skills and CAO test results by gender

	MCT (%)		PSVT (%)		CAO MATHS		CAO DCG		CAO ENR	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
N	731	147	451	118	639	120	206	17	182	7
Mean	39.17	33.47	63.92	52.57	48.22	59.54	69.83	70.29	75.03	77.14
sd	19.050	17.692	23.296	26.136	28.126	29.039	15.698	10.227	13.302	8.092

	CAO CHM		CAO Phys		CAO TEC		CAO AMT		CAO ENGL	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
N	67	39	204	25	44	1	30	5	642	123
Mean	48.73	58.52	53.65	62.20	72.95	75.00	54.50	63.00	53.98	62.28
sd			14.597	16.651	11.828	.	13.918	17.889	17.801	16.097

Design and Computer Graphics

As noted above, there is a strong correlation between the Design and Computer Graphics (DCG) test scores and the scores on both spatial skills tests. This course teaches freehand sketching, traditional drafting, and CAD and develops problem solving and creative thinking skills through the analysis and solution of 2- and 3-D graphics (Minister for Education and Skills, 2014). Upon closer examination of spatial skills test results, students who took the DCG test outperformed the students who did not take the DCG test. The means MCT and PSVT:R scores and standard deviations are shown in Table 5 and

Table 6 for the of the DCG testers and non-testers.

A two-way ANOVA was used to examine the effects of gender and DCG experience on MCT and PSVT:R scores. The student sample was divided into two groups: those who took the DCG leaving certification and those who did not take the DCG leaving certification. For the MCT test, the test of between-subject effect shows a significant main effect of the DCG experience on the MCT test score, F(4,883)=30.57, p<0.001. The effect size (Cohen's d) of the DCG experience is 0.74 for females and 0.76 for males, which is borderline large. A similar trend is observed for the PSVT:R test. A significant main effect of the DCG experience on the PSVT:R score is seen, F(4,565)=16.73, p<0.001. The effect size (Cohen's d) of the DCG experience is 0.57 for females and 0.58 for males.

Table 5. MCT Scores disaggregated by gender and DCG status

	Male			Female			Total		
	No DCG	DCG	Total	No DCG	DCG	Total	No DCG	DCG	Total
Mean	35.38	49.00	39.06	31.94	45.18	33.47	34.71	48.70	38.13
sd	17.497	19.533	19.044	17.275	16.898	17.692	17.494	19.332	18.932
N	540	200	740	130	17	147	670	217	887

Table 6. PSVT:R Scores disaggregated by gender and DCG status

	Male			Female			Total		
	No DCG	DCG	Total	No DCG	DCG	Total	No DCG	DCG	Total
Mean	61.42	72.24	63.92	50.82	76.67	52.57	58.87	72.56	61.56
sd	23.586	20.281	23.296	26.115	9.258	26.136	24.611	19.707	24.328
N	347	104	451	110	8	118	457	112	569

Among the students who did not take the DCG test, there is a significant difference between male and females on both the MCT and the PSVT, favouring males. For the MCT, F(1,660) = 4.212, p=0.041. For the PSVT, F(1,455) = 16.014, p<0.001. It is interesting to note that there is also a significant difference in Mathematics scores in this group, favouring females, F(1, 540) = 18.691, p<0.001.

Among students who did take the DCG test, there is no significant difference between males and females on either of the two spatial skills tests (MCT and PSVT:R). There is also no

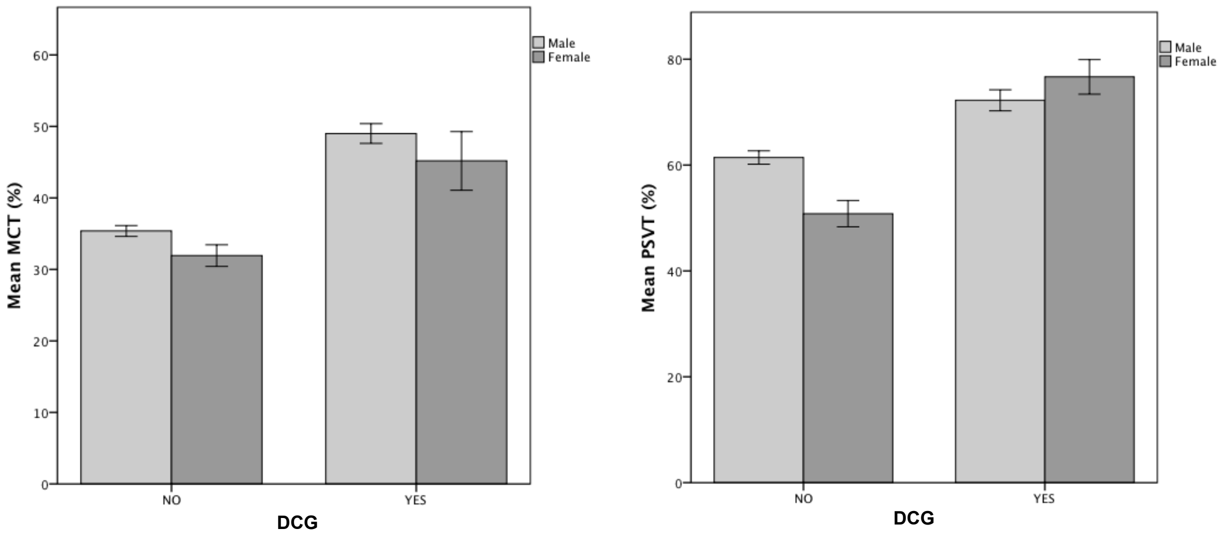

Figure 2. MCT and PSVT Scores for non-DCG Takers and DCG Takers, by gender

significant difference between males and females' mathematics leaving certificate scores for the DCG-takers. The mean scores for the MCT and PSVT:R tests, for non-DCG takers and DCG-takers, by gender, are shown Figure 4. A limitation of this analysis is the very small number of female students who took the DCG test (N=8). This is indicative of a deeper problem that females accounted for only 7% of the overall number of DCG test-takers in the country (State Examinations Commission, 2009). Further, only 1,257 took the DCG leaving certification examination, out of a total of 43,000.

Findings, Implications, and Future Work

Students who took the Design and Computer Graphics leaving certification performed significantly better on both the MRT and the PSVT:R than students who did not take the DCG leaving certificate. Significant gender differences, favouring males, were observed among students who did not take the DCG leaving certificate. However, this gender gap was not observed among the students who took the DCG leaving certificate. This finding is particularly significant in light of the most recent data indicating that less than 3% of students take this leaving certificate and females comprise only 7% of the overall number of students taking the DCG leaving certificate. Since spatial skills are known to be important to academic and professional success in STEM, the implications of this finding with regard to educational access are important.

These findings suggest several avenues for future research. Further investigation with a larger and broader sample of students is required to understand the relationship between the DCG experience and spatial ability. Research is required to illuminate the relationships between abilities and preferences, third-level selection, and third-level academic success. Consideration should be given to the design and placement of targeted spatial skills instruction to increase academic success in third-level engineering and science.

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