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Examining the Relationship Between Physics Students' Spatial Skills and Conceptual Understanding of Newtonian Mechanics

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***Abstract**: One of the primary motivating factors of physics educators is to ensure a high level of conceptual understanding is achieved by their students. Furthermore it has been shown that success in physics and engineering courses is strongly related to students' spatial skills. Conceptual and spatial skills tests have been independently developed and reported in the literature as a measure of each of these competencies. In this study we examine correlations between spatial skills and conceptual understanding using two of these tests in order to determine the relationship, if any, between students' conceptual understanding of Newtonian mechanics and their spatial skills. Spatial skills and Conceptual understanding of physics are tested using the Purdue Spatial Visualisation Test of Rotations (PSVT:R) and the Force Motion Concept Evaluation (FMCE) respectively. Correlations between PSVT:R and FCME scores are presented along with significant gender biases in both test scores.*

Introduction

Physics is an important subject in most Science Technology Engineering Mathematics (STEM) courses. As such physics and specifically Newtonian Mechanics (NM) is introduced to first year students in many third-level STEM courses. Furthermore concepts in NM form the foundations on which many more advanced topics in physics and engineering are built. Therefore a strong understanding in NM is desirable in physics and engineering students and could assist in their future success in their chosen subject.

Spatial skills have been widely linked with success in STEM disciplines (Humphreys, Lubinski, & Yao, 1993; Sorby, 2009). Studies have reported improved academic performance and retention in groups who received spatial skills training (Veurink & Sorby, 2011). Gender differences in spatial skills, favouring men, have been noted in many studies (Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000; Debelak, Gettler, & Arendasy, 2014; Halpern et al., 2007; Maeda & Yoon, 2013; Voyer, Voyer, & Bryden, 1995).

Problem solving in physics often requires visualising complex situations, abstract concepts, and graphical representations alongside imagining a change in parameters. In a study investigating students solving of kinematics problems it was shown that students with high spatial skills are better equipped to solve physics problems of this type (Kozhevnikov, Motes, & Hegarty, 2007). Spatial ability training of gifted STEM students reported an increase in physics performance over other STEM subjects (Miller & Halpern, 2013). Furthermore, a study investigating physics learning by students of different spatial skills has shown a correlation between NM and spatial skills (Kozhevnikov & Thornton, 2006). Kozhevnikov *et al.* employ the Force Motion Concept Evaluation (FMCE) test (Thornton & Sokoloff, 1998) as a measure of conceptual understanding of NM and the Paper Folding Test (Ekstrom, French, & Harman, 1976) as a measure of spatial skills. The sample tested was an undergraduate class taking general non-calculus physics course. In this study we test a large sample of physics students set across different years and different academic levels to investigate whether a correlation exists between spatial skills and conceptual understanding of NM. The relevance of different categories of conceptual questions to spatial skill ability is examined. Results are also examined to investigate gender imbalance in both spatial skills and conceptual understanding.

Methodology:

This study was conducted at the Dublin Institute of Technology during the academic year 2014/15.

Participants

The majority of students studying physics in the School of Physics were tested. A full list of the courses tested is shown in Table 1. All first year classes were tested during their first week of study to get a snapshot of their level of physics understanding and their spatial skills before the start of their third level education. The second and third year classes were tested at the end of their first semester before the winter break. The fourth year classes were tested in the first week after their return from winter break. The reason for the dispersed testing for the second to fourth year students was due to their class and exam timetable. Students across all years and both level 7 and level 8 (Quality and Qualifications Ireland, 2014) students were tested to get a full picture of the variance in physics understanding and spatial skill level of students studying physics in the School. Both physics and chemistry majors are accounted for in the 4th year DT227 students. The 3rd year chemistry majors in DT227 where omitted due to timetable constraints. The level 7 students in 1st year enter through a general entry programme and choose at the end of first year to enter a discipline specific degree programme. Overall the students are 37.2% female and 62.8% male, although some students may have not taken both exam and will be included in all following analysis except for correlation between tests.

Table 1. List of programmes tested.

Programme Code	Title	Years	Academic level [a]
DT222	Physics Technology	1-4	8
DT227	Science with Nanotechnology	1-4b	8
DT235	Physics with Medical Physics & Bioengineering	1-4	8
DT221	Physics with Energy and Environment	1-3c	8
DT212	Science	1d	7

[a] Level defined by Irish National Framework of Qualifications (Quality and Qualifications Ireland, 2014); level 7 is an ordinary degree programme and level 8 is a honours degree programme

Spatial Test

A variety of test instruments are available to measure different aspects of spatial ability (Bennett, Seashore, & Wesman, 1973; CEEB, 1939; Vandenberg & Kuse, 1978) . Tests of three-dimensional spatial ability are of particular interest in STEM education and have been most widely used in STEM education studies. The students' 3D rotational spatial skills were measured using the Purdue Spatial Visualization Test: Rotations (PVST:R) (Guay, 1976). It contains 30 multiple choice questions. Each question first presents the subject with a sketch of a 3D reference object before and after the object has been rotated about one or more axes. A picture of a second reference object is shown with five possible solutions. The subject must choose which of the five solutions matches the second reference object after being subjected to the same rotations as the first. The students were given 25 minutes to complete the test as is recommended with the accompanying test instructions.

Newtonian Mechanics Concept Test

It is often difficult to examine students' conceptual understanding in physics with many university exams testing content and students ability to do mathematical manipulations with physics equations. Concept tests such as the Force Concept Inventory (Hestenes & et al., 1992) and the Force Motion Concept Evaluation (FMCE) have been developed to measure students' conceptual understanding of Newtonian Mechanics. The FMCE consists of 47 non-numerical multiple choice questions. This test has been validated by a large number of studies to measure students understanding of NM (Ronald, Dennis, Karen, & Jeffrey, 2009; Thornton & Sokoloff, 1990, 1998). These are further subdivided into seven different sub-topics and a set of diagnostic questions disregarded in studies on conceptual understanding. Cluster scoring and all-or-nothing scoring system is implemented to account for false positives in the subjects answers (Smith & Wittmann, 2008). Students were allowed up one hour for the FMCE tests although very few, approximately less than 5%, students took longer than a half hour.

Results and Discussion

Descriptive statistics for the FMCE and PSVT:R scores are shown in table 2 and the mean scores in FMCE and PSVT:R are shown in figure 1 (a) and (b) respectively. A one-way analysis of variance revealed significant differences in rotational spatial skills between males and females, for the PSVT:R, $F(1,180) = 18.576$, $p=0.00$. Due to inhomogeneity of the variance in FCME scores the more robust Welch test showed a significance of $p=0.002$. Therefore significant differences favouring males exists in both physics understanding and spatial ability. These results reflect reports of gender imbalance in spatial skills and NM conceptual understanding (Madsen, McKagan, & Sayre) in the literature.

Table 2. Partial correlation matrix showing the correlation for PSVT:R with topics tested within the FCME

	Male			Female		
	n	M	SD	n	M	SD
PSVT:R	113	69.95	21.68	69	55.42	22.67
FCME	117	25.84	24.65	68	16.44	15.55

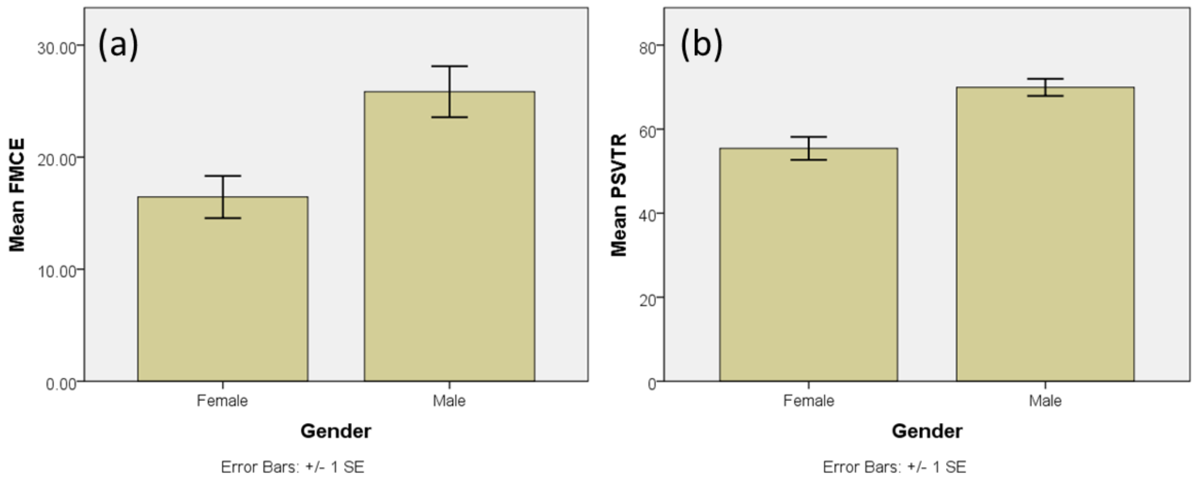

Figure 1: (a) Mean FCME scores and (b) PSVT:R scores

Figure 2 plot separates FCME score (a) and PSVT:R score (b) into year and level, error bars show the standard error and are not included in the 4th year female group as this is bar represents a single student. Figure 2(a) illustrates a higher average score for the level 8 first years versus the level 7 students. This may be explained by the higher academic credentials of the level 8 students.

A clear increase in average score in the male group is seen between the first and second year. This is to be expected as Newtonian mechanics is taught in first year. However, this is not a longitudinal study and therefore these are not the same student cohorts. We would also expect the score to increase in the following years, although NM is not revisited as a subject the concepts would be discussed in other subjects that rely on the principles of NM. A gender bias in FMCE favouring men is suggested in every year. Additionally and disappointingly the female group do not show an increase in mean score outside the standard error between year 1 and 2. This would suggest an interesting study to investigate a hypothesis of whether high rotational spatial skills somehow pre-dispose the students to a better learning of spatial skills. Previous correlation studies found a correlation between spatial skills and FCME score before NM instruction but not after (Kozhevnikov & Thornton, 2006) would seem to contradict that hypothesis but different spatial skills where tested with different cohorts taught differently. The gender bias is evident in the PSVT:R mean score , figure 2 (b), across all years and the spatial skills of the student groups appear to remain consistent across the four years.

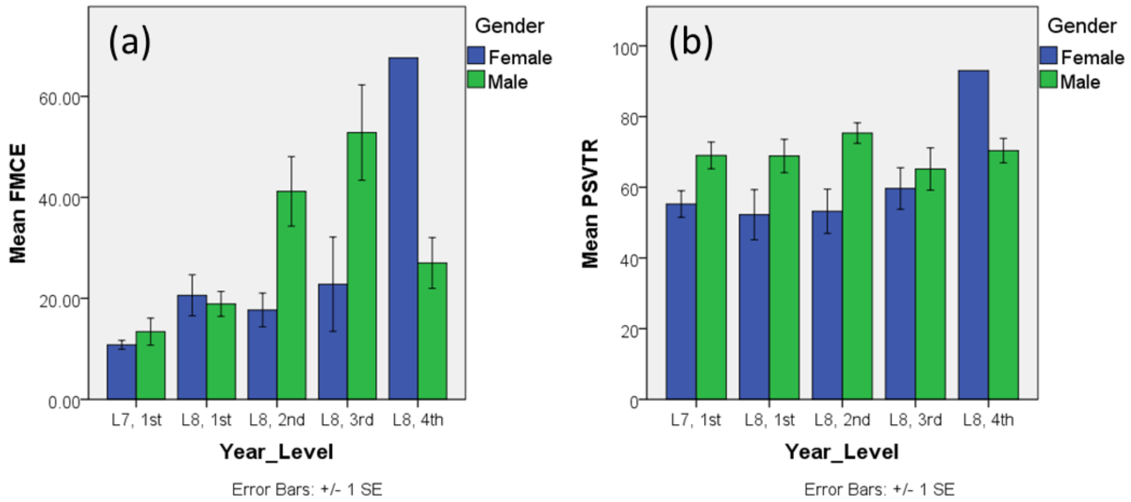

Figure 2: (a) Mean FCME scores and (b) PSVT:R scores shown for different academic levels and year of study. Error bars are one standard error. No error bars are placed on the level 8 4th year female score as this represents a single student

Gender, level and year scores illustrated in figure 2 suggest a correlation between FCME and PSVT:R performance. Correlation tests reveal a statistical significant correlation between FCME and PSVT:R scores with a significance of <0.001 and a Pearson Correlation coefficient of 0.295 with a sample size of N=173. The clustering of questions within the FMCE tests allows the testing of students understanding of seven separate clusters within NM. Correlations between spatial skills and these sub-topics are reported in table 2, were N=173 for all columns. Significant correlations are reported in all of the topics tested. Questions asked are non-numerical and rely on plain language with pictorial and/or graphical cues. Some topics such as force are represented twice, firstly using plain language and diagrams and again employing graphical representations. Greater correlation is evident in question clusters using graphical representation than those which do not employ graphs. A relatively large correlation is also evident in the cluster Reverse Direction, in these questions students need to imagine a body which has a turning point in its trajectory.

Table 3. Partial correlation matrix showing the correlation for PSVT:R with topics tested within the FCME

	Force	Reverse Direction	Force Graphs	Acceleration Graphs	Newton's 3rd law	Velocity Graphs	Energy
Pearson Correlation	.184*	.198**	.208**	.279**	.179*	.254**	.265**
Sig.	0.016	0.009	0.006	0.000	0.019	0.001	0.000

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

A scatter plot of PSVT:R scores against FMCE scores as shown in figure 3 illustrates the large variance of spatial skills across the years. If divided into quadrants as shown it is clear that is very unlikely to have low rotational spatial skills and a good understanding of NM, as measured by the FCME.

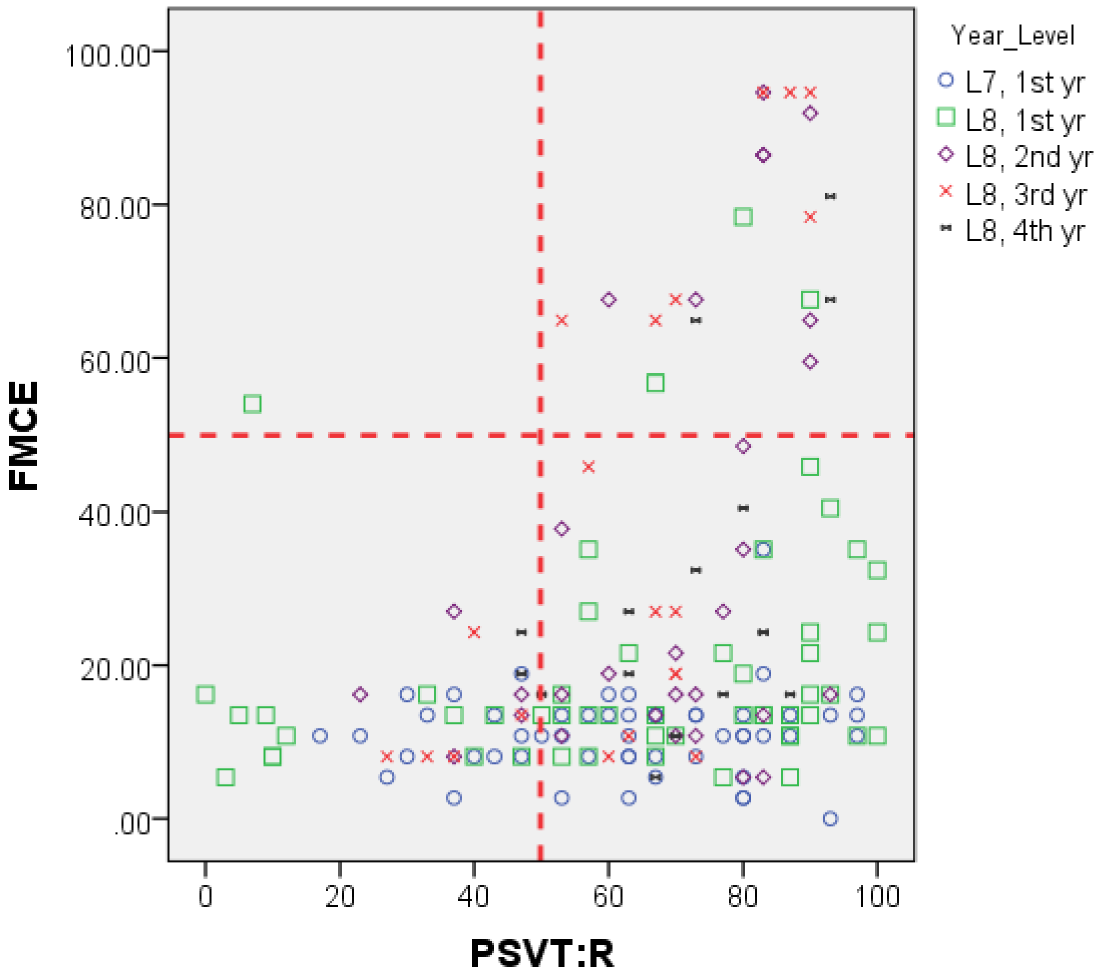

Figure 3: Scatter plot of FCME and PSVT:R scores for all students and all years, line are drawn to illustrate the relative populations in the four quarters.

Conclusions

Rotational spatial skills are often linked with success in STEM subjects. It is hoped a strong understanding of physics would be an indicator of success within a physics degree, therefore it would be reasonable to expect a correlation between spatial skills and physics. It is clear that there exists a correlation for the students tested between rotational spatial skills and Newtonian mechanics as measured by the PSVT:R and FMCE tests. In fact significant correlation is reported between PSVT:R and all the different question clusters within the FMCE. Perhaps this is unsurprising given the pictorial and graphical nature of the questions. In question clusters dealing with graphs and changing trajectories the correlation is largest as measured by the Pearson coefficient.

A difference in physics understanding exists between first and second year students. This is expected as this is pre- and post-instruction of Newtonian Mechanics. This significant difference does not exists with the female group and raises the suggestion that perhaps high spatial skills pre-disposes students to a greater understanding of NM or assist with the learning of NM concepts however further studies would be required to investigate this issue.

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