What do we *really* want to know about spatial visualisation skills among engineering students?

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***Abstract**: We used two well established tests, the Mental Cutting and Mental Rotation Tests, with a group of 90 1st year engineering students before and after classes in engineering drawing. Our intention was to find out how our students compare with other groups who have taken the same tests, and to assess the impact of our engineering drawing classes. The results were disappointing, in that neither their previous tuition nor our tuition seems to have made a significant difference to the test scores. However, revisiting the literature on these tests raises some questions about what we were measuring and why. Perhaps we should be focusing on a more holistic approach to professional skills in spatial visualisation, and evaluating the development of these skills throughout the full undergraduate degree, rather than thinking in terms of abilities that can be measured by simple tests and improved by a few classes.*

Context

The University of New South Wales (UNSW) runs 1st year introductory design classes as a foundation for 1350 undergraduate engineering students each year. This is a project-based course where students are introduced to the design process and to some of the skills they will be building throughout their degree. These skills include basic technical sketching and drawing. The1st year engineering students have a record of academic achievement in high school science and mathematics. However, the majority have had no formal training in technical drawing. Although the admission process can also take into account evidence of activities experience in practical engineering, this is not an entry requirement (Russell & Spralja, 2009).

Anecdotal accounts from those teaching undergraduate engineering in UNSW indicate that our students vary widely in their ability to use CAD software intelligently. By ‘intelligently’ we mean the ability to solve problems requiring reliable mental modelling and manipulation of 3D shapes and their 2D representations. Such spatial visualisation skills would, for example, imply the ability to control the software representations rather than accept default results uncritically. We have questions about whether, sketching, hand drawing, CAD practice, or some combination of these is the best way of developing this ability. We also question whether the 4 hours of specific tuition in engineering drawing (2 h lecture and 2 h guided practice in tutorials) that we provide is sufficient in the 1st semester of engineering study.

So we decided to find out more about what skills our students arrive with, and how we are starting to develop them in 1st year engineering teaching.

Literature on spatial visualisation

Sorby (2007) notes that many university students have difficulties with the 3rd and highest level of spatial cognition development as defined by Piaget – visualizing areas, volumes and distances in combination with translations, rotations and reflections. Sorby also notes that incoming students will vary widely in how they have developed their spatial skills, because they have different experience in eye-to-hand coordination activities such as 3D computer games, sports, mathematics and construction toys. These different experiences may account for the widely reported gender differences in spatial cognition (e.g. Cooke-Simpson & Voyer, 2007; Lawton, 1994; Vandenberg & Kuse, 1978).

Sutton & Williams (2008) suggest using a range of tests for this ability, including measures such as the Mental Rotation Test (MRT), the Mental Cutting Test (MCT) and the Differential Aptitude Test (DAT). A European study used the MRT and the MCT to measure development of spatial visualization skills among 1st year engineering students across 3 universities (Leopold, Gorska, & Sorby, 2001). This study found that both the MRT and the MCT were significant predictors of success in final examinations, but that there were differences between universities. The tuition in the 3 universities varied in the proportions of descriptive geometry, graphics and CAD, but in all cases involved between 30 and 40 hours of tuition over a semester. The study concluded that a stress on hands-on sketching and drawing improves spatial ability more than a stress on CAD.

A study in Spain (Martin-Dorta, Saorin, & Contero, 2008) used a web version of the MRT in conjunction with the DAT to measure the effectiveness of a 12 hour remedial course using Google Sketch-up CAD software. The results were compared with those from other types of remedial course, each with 6 hours of tuition, and found the CAD tuition was effective. Similarly, Watkins (2005) finds that while board drawing exercises are no longer necessary for developing engineering drawing skills, hand sketching is still valuable.

Another study in a Spanish university used qualitative methods to find out why 50% of students were failing a 1st year engineering graphics course (Garmendia, Guisasola, & Sierra, 2007). The study involved semi-structured interviews with 12 students, in which the students were asked to solve visualization problems 'out loud'. The interviewees were selected randomly and had all passed the course, which involved 60h of lectures and practical drawing sessions – far more than in the UNSW context. However the authors note that the tuition involves mainly note-taking and relatively little active participation. Despite having had much tuition and having passed the course, some students were still trying to solve problems by trial and error or intuition. The same study also reviewed technical drawing textbooks and found that none presented a clearly structured explicit process for solving visualization problems.

These qualitative findings suggest that some of the spatial visualization skills that are being measured in standard tests may involve what Perkins(1999) identifies as 'troublesome knowledge' that is hard to communicate. Such knowledge often includes discipline-specific 'threshold concepts' (Meyer & Land, 2005) that are hard for teachers to recognize. Once acquired, a threshold concept transforms thinking irreversibly so a successful learner (and a teacher) may not be able to imagine how they thought before, especially if the concept has not been explicitly taught. As learners "we often get the hang of enquiry in a discipline without having a clear reflective idea of what we are doing" (Perkins, 2006, p40).

Two of the most commonly used spatial visualization tests have long histories. The MCT dates back to 1939, and is based on the traditional engineering discipline of 'descriptive geometry' (Leopold, 2005). Longitudinal tests with engineering students in Monash University found that those who had taken a 52 h course significantly improved their scores in this test (Field, 1999). A study involving 163 1st year engineering students in Brazil found a relationship between the MCT scores and performance in technical drawing (Adanez & Velasco, 2002). These results were similar to those obtained for Japanese students (Sun & Suzuki, 1999). As with the MCT, early use of the MRT (Vandenberg & Kuse, 1978) found that it compared well with (i.e. was consistent with) other tests of spatial visualization. Later researchers, as noted above, have used it in conjunction with other tests. Table 1 lists results from previous use of the MCT and MRT tests with undergraduate students.

While there are differing opinions on what type of tuition is most effective, it seems that the measured improvements in the quantitative studies are associated with tuition in which the students have many hours of hands-on structured exercises, far more than the 4 hours in our own introductory design classes. It could be that the hands-on activities, whether using CAD or hand drawing, or perhaps developed through other activities such as sports, hobbies or 3D computer games, are working in ways that we do not fully understand. The quantitative tests tell us only about the outcome, not the process.

In this paper we describe what we found out about the impact of tuition, before and during 1st year undergraduate study, on student scores in standard spatial visualisation tests. We also come to some conclusions on what the tests did not tell us, and what further research is needed.

Table 1. Reported MCT and MRT scores before and after tuition (SD where available)

source	*n*	pre-score	post-score	engineering design tuition between pre and post scores
MCT scores				
(Sun & Suzuki, 1999)	?	12.5 (4.5)	17.8 (4.7)	simulator experiment course 1.5 and 3h/week over 2 semesters
(Sun & Suzuki, 1999)	?	11.9 (3.8)	16.2 (9.8)	control course 1.5 and 3h/week over 2 semesters
(Field, 1999)	25	17.7 (5.2)	18.3 (5.1)	special course in spatial visualization, 1994
(Field, 1999)	11	15.9 (4.5)	14.9 (5.5)	control 1994
(Field, 1999)	39	15.7 (5.0)	18.4 (3.9)	special course in spatial visualization, 1995
(Field, 1999)	16	14.9 (5.5)	16.6 (5.3)	control 1995
(Leopold, et al., 2001)	220	63.8% (20.4)		descriptive geometry up to 60 h
(Leopold, et al., 2001)	198	59.8% (19.3)		descriptive geometry up to 45 h
(Leopold, et al., 2001)	57	57.6% (18.6)		up to 40 h
(Sorby, 2007)	186	37.9%	51.4%	traditional spatial skills course2h/week for a semester
(Sorby, 2007)	61	34.4%	50.4%	multimedia spatial skills course 2h/week for a semester
MRT scores				
(Vandenberg & Kuse, 1978)	115	20.1		male psychology students, no tuition
(Vandenberg & Kuse, 1978)	197	13.2		female psychology students, no tuition
(Martin-Dorta, et al., 2008)	12	10.6 (4.3)	16.8 (7.8)	12 h course using Google Sketch-up
(Martin-Dorta, et al., 2008)	17	8.2 (4.6)	13.5 (6.1)	6 h paper and pencil
(Martin-Dorta, et al., 2008)	15	9.6 (4.5)	13.3 (4.8)	6 h web-based tuition
(Martin-Dorta, et al., 2008)	20	7.9 (3.6)		6 h sketch-based modelling
(Martin-Dorta, et al., 2008)	40	19.2 (7.6)	24.5 (8.5)	12 h course using Google Sketch-up
(Leopold, et al., 2001)	220	63.3% (21.8)		descriptive geometry up to 60 h
(Leopold, et al., 2001)	196	61.4% (22.2)		descriptive geometry up to 45 h
(Leopold, et al., 2001)	55	61.3% (19.4)		up to 40 h
(Sorby, 2007)	186	61.9%	71.9%	traditional spatial skills course2h/week for a semester
(Sorby, 2007)	61	53.0%	72.8%	multimedia spatial skills course 2h/week for a semester

Methodology

Since our students have only 4 hours of structured tuition in engineering drawing in their initial course, we wanted

a. to compare their scores for standard tests with other student groups reported in the literature

b. to find out how our initial tuition and the students' previous tuition would influence the scores.

With any educational research in a live teaching context, there are limits to the types of controlled experiment that can be done. Nevertheless, in order to answer our first question, which is about how our students compare with previous studies, we decided to ask a group of students to complete the MRT and MCT tests and to compare their scores with the documented scores for other groups. We chose these tests because of their availability and their established history, and because it was possible to run them under comparable conditions.

As far as possible we replicated the standard conditions of previous tests, offering the same tests online using the quiz facility in our learning management system, with a strict time limit. Students had an opportunity to read the instructions and try a sample test before beginning the timed tests. They were told that they would get a few marks for completing the tests, regardless of their scores, and that the scores would be an indication of their skills for engineering drawing. We also asked students to indicate whether they had any previous experience of formal education in engineering drawing, and for their consent to use the data in a publication.

The MRT test consists of 20 questions. Each question shows a 2-dimensional representation of a 3-dimensional object seen from one angle. The task is to select two options from four other representations in which two are the same object rotated. The two incorrect options are the mirror image shape rotated. Both selections have to be correct to gain a point. The test was run in two parts, allowing 3.5 minutes for each.

The MCT has 25 questions and takes 20 minutes. Each question shows a 3-dimensional object seen from one angle, with a plane cutting through it. The task here is to select one of four options that represents most accurately the plane of the cut.

We did not collect information on age or gender. Despite the frequent mention in the literature of gender as a persistent influence on scores in these tests, we agree with Sorby (2007) that this is a red herring, in that we cannot know whether these differences are socially or genetically determined. Nor have we considered any developmental or age-related factors. Our main interest is in how all our students' abilities can be improved, given that they have chosen to study engineering, and that we do not require formal qualifications in engineering drawing as a condition of entry.

The students who were asked to complete the tests were the mechanical engineering and mining engineering project groups within our common 1st year engineering design course – a total of 212 students. The two groups had common classes in engineering drawing. However, we only included in the analysis the scores from those students who completed both tests before and after the engineering drawing classes, and who also explicitly consented to both score sets being used for this study.

The analysis process involved calculating and comparing the means and standard deviations of the scores and testing the significance of differences between:

- before and after scores
- those with and without prior tuition in engineering drawing.

Results

From the group of 212, we found that 89 had completed both tests in full, before and after drawing tuition, and had also explicitly consented to their scores being included in this study in both cases. The results are listed in Table 2. MCT1 and MRT1 are scores before tuition and MCT2 and MRT2 are scores after tuition.

Because a significant number of students had lower MCT scores the second time, we also looked at how much time students spent on the tests. We found that on the first run most students took the full 20 minutes allowed, but on the second run, most students took only 10-15 minutes.

Over all, it seems that, while tuition in engineering drawing, both before and during 1st year study has some effect on the test scores, that effect is fairly small and not significant. Also, our students' scores vary widely like those of other groups of 1st year engineering students reported in the literature.

Table 2

	with experience				*without experience*			
	MCT1	*MRT1*	*MCT2*	*MRT2*	*MCT1*	*MRT1*	*MCT2*	*MRT2*
Mean	15.54	11.27	15.25	12.92	12.31	9.26	13.14	11
Standard Deviation	5.29	3.69	6.66	4.34	5.59	3.57	5.90	4.54
n	24	24	24	24	65	65	65	65
Confidence Level (95.0%)	2.23	1.56	2.81	1.83	1.38	0.88	1.46	1.12

Discussion and conclusions

Previous studies have shown that only courses involving substantial 'time on task' resulted in a measurable change in spatial visualisation test scores. So it is not surprising that our limited 4 hours of introduction to engineering drawing, with a few follow-up drawing tasks in the weeks between tests, has little effect, and that group of students who reported having had previous tuition in engineering drawing had slightly higher scores in both tests. Our results are consistent with this, in that the differences were smaller than changes reported in the literature as resulting from substantial courses in engineering drawing.

However the main outcome from our study so far is a number of further questions, both about the methodology and testing methods used, and about the relevance of the questions that we started out with. The outcomes reported here can therefore be considered as part of a reflexive research strategy (Alvesson & Sköldberg, 2000), in which we are now re-evaluating some of our initial assumptions, and reframing our questions.

One of our assumptions, based on the extensive literature, was that the MCT and MRT tests are predictors of spatial skills required in engineering design, as measured in formal assessment tasks. Yet students who have passed some formal courses also showed deficiencies in skill, when their spatial problem solving was investigated qualitatively through in-depth interviews in which they talked through their problem-solving strategies (Garmendia, et al., 2007). This qualitative work, along with the UNSW results reported here, is consistent with the suggestion that spatial visualisation involves some troublesome and tacit knowledge that could be described as 'threshold concepts'. Such an interpretation would suggest a strategy of providing more analytical and structured presentation of problem solving, to help those who are still struggling with the spatial threshold concepts. On the other hand, Sorby (2007) suggests that higher levels of spatial expertise are characterised by holistic strategies, which could be harder to articulate as structured step-by-step thinking. Overall, this leaves us with two questions:

1. What is the relationship between the various psychometric tests, assessed undergraduate engineering drawing tasks and the skills actually used in professional engineering design work?
2. Is there a way to provide more structured tuition to develop these skills faster, or is it simply a question of time on task?

Reflecting on the student response in the 2nd MCT test, we now also question the benefits of running tests such as the MRT and MCT separately from formal assessment, as diagnostic and analytical tools. Our 1st year engineering students are required to use engineering drawing skills in assessed activities, and we could perhaps make our assessment criteria reflect more explicitly the development of spatial visualisation skills. We need more information about students' perceptions and motivations in relation to this. So a third question is:

3. Are the psychometric tests for spatial visualisation a useful as a way of providing structured feedback to undergraduate students on their skills development?

Answering this 3rd question will require qualitative research to find out in more depth how our students are reasoning when they solve 3D problems, and how their reasoning develops throughout their study as they gain more experience of hands-on design work using CAD and other tools.

A number of other specific studies could possibly help answer these questions, such as:

- interviews with students who take the psychometric tests, to assess not only how they go about answering, but also how motivated they are to score well when this does not gain them marks
- comparative studies on test scores at different points in undergraduate skill development
- use of a broader range of tests for quantitative assessment
- research with professionals who are highly skilled in spatial visualisation, involving both the psychometric tests and qualitative study to elicit some of their tacit problem solving strategies.

So in conclusion, our initial foray into measuring our students' spatial visualisation skills has made us aware of the need to investigate these skills as part of a more complex learning context, in which there is a need for both quantitative and qualitative analysis.

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