Developing a discipline-based measure of visualisation

Ken Sutton, Faculty of Science and Information Technology, and **Anthony Williams**, Faculty of Engineering and Built Environment, The University of Newcastle, Australia
Ken.Sutton@newcastle.edu.au Tony.Williams@newcastle.edu.au

Abstract: *This paper reports on current studies in a large research project concerned with assessing and improving visualisation specific to engineering and science disciplines. These studies primarily focus on establishing a reliable measure of visualisation to identify poor performers so that training and learning tasks can be developed. The visualisation measure called the 3D Ability Test (3DAT) complies with psychometric test construction standards and consists of subtests and test items within each. The 3DAT is a computer-based instrument that measures choice accuracy and response time. The methodology used to investigate subtest properties is presented and results of statistical procedures are reported. Factors of visualisation are examined and the benefits of using a range of subtests are outlined. A case is made for a purpose-designed subtest (dot coordinate) to be seen as a particularly good measure of the visualisation skills considered necessary for science-related disciplines. We outline preliminary studies conducted with unskilled participants (no prior learning) and skilled participants (prior learning) under laboratory conditions. Included is research done with first year university students in design-based disciplines such as mechanical and chemical engineering. Results revealed significant differences between engineering groups when compared to other groups and consistent evidence of gender bias favouring males. The success of collaboration between unusual partners (applied psychology and design) is discussed and argued is the relevance of visualisation to science disciplines where conceptual development is important. Central to the overall project is funding provided by the Australian Learning and Teaching Council (ALTC).*

Introduction

One of the more important aptitudes for students studying science and engineering courses is spatial ability, often referred to as simply visualisation. Spatial ability can be defined (Sutton and Williams 2007) as the performance on tasks that require:

- the mental rotation of objects,
- the ability to understand how objects appear in different positions**,** and
- the skill to conceptualize how objects relate to each other in space.

A substantial part of spatial ability is three-dimensional (3D) understanding. 3D understanding is the ability to extract information about 3D properties from two-dimensional (2D) representations (Sutton, Heathcote and Bore 2005). This skill requires perceptual abilities to interpret what is seen, and spatial abilities to mentally manipulate graphical representations.

Importance of Visualisation to Science

Sorby (2006) reports evidence that 3D spatial skills are critical to success in a variety of careers, including engineering and science. Her research reveals the importance of advanced spatial reasoning and visualisation skills to these disciplines, although these skills are not handled well by many novices. There is also evidence of high failure rates in these types of courses and evidence to support the value of early spatial ability training. Sorby also identified a gender bias against females in spatial performance. Despite there being a vast amount of research on spatial ability, there is very little known about the effects of spatial ability on science and engineering and how it is developed through appropriate education programs. Furthermore, previous research in spatial ability tends to focus on one or two test types and neglects test types that specifically target spatial cognition relevant to science and engineering disciplines (Allahyar and Hunt 2003). These findings emphasise the need for further research into higher spatial thinking (Sutton and Williams 2006).

Many science disciplines have aspects of visual skills in them. Whenever there is the need to consider visual information and extract detail from this, there is a need to have a comprehensive understanding of the relationship of parts of the visual information to each other. Examples of this might include the need for a Chemist to understand the relationship of atomic structures in molecules or a Biologist coming to terms with the physical dimensional relationship of components of an organism. The issue of heuristic understandings is not outside the domain of the sciences and spatial abilities are important in understanding such concepts.

Factors of Spatial Ability

According to Maier (1998), there are 5 main factors of spatial ability:

Spatial relations (SR) refers to the perception of a target object in relation to another on a dimension such as size, distance, volume, order, position or other distinguishing feature

Spatial perception (SP) is the ability to determine spatial relationships among objects despite distracting information. More specifically, SP is the ability to mentally fix the vertical or horizontal position of an object which is depicted at varying degrees of orientation.

Spatial visualisation (SV) is the ability to mentally manipulate, rotate, twist, or invert visually presented stimuli. This may involve imagining the rotations of objects in space.

Mental rotation (MR) refers to the ability to mentally rotate visual images. These images may be two-dimensional or three-dimensional.

Spatial orientation (SO) is the ability to orient oneself physically or mentally in space. A person's spatial position is essential to this task.

In general, there is support for a five-factor model though there is some debate in the literature about this. Overlap is mostly acknowledged and there is some argument about there being two principle factors such as SR and SV. Others consider MR and SP to be the principle factors.

Why a Specific Test of Visualisation

There is a need to benchmark spatial ability specific to engineering (Adanez and Velasco 2002). Most existing visualisation tests are generic and are seen as part measures of general intelligence. Research in visualisation tends to focus on one or two test types, and in particular, tests that involve mental rotation. These tasks are non-specific though regarded by many as standard measures of visualisation. What is needed instead is a test that targets the skill set required by engineering students in the graphical communication courses they undertake (Allahyar and Hunt 2003). Substantial research indicates the importance of visualisation and that there is no ideal test that will accurately profile the spatial ability of engineers and scientists. We believe that an accurate measure of visualisation for engineering and science should consist of multiple test types rather than any one particular test type.

The main study reported in this paper is considered a lead-in study for a larger project made possible by a grant from the Australian Learning and Teaching Council (ALTC). This funding allows a comprehensive focus on measuring and improving visualisation for science and engineering-based disciplines across the higher education sector. The process so far has been two-way in that information from the larger project has contributed to the lead-in studies while the outcomes from the lead-in studies are providing stepping stones for the larger project.

Science and Engineering Nexus

The sciences are a fundamental basis on which the engineering curriculum is built, and traditionally the term 'engineering sciences' was used to identify this relationship. The relationship between the sciences and engineering is clearly established in the Engineers Australia accreditation requirement that all engineering degrees ensure that their graduates develop, to a substantial level, the generic attribute: ability to apply knowledge of basic science and engineering fundamentals. Further, in accordance with the Accreditation Policy of Engineers Australia (www.engineersaustralia.org.au/), a four-year professional engineering program would be expected to include a total learning experience of not less than 40% in mathematics, science, engineering principles, skills and tools appropriate to the discipline.

The underlying importance of sciences in engineering is emphasised in Nguyen's (1998; p.65) statement: 'Engineering is a profession directed towards the application and advancement of skills based upon a body of distinctive knowledge in mathematics, science and technology'.

In order for engineers to function effectively in a multidisciplinary environment, engineering education must have the capacity to instil its graduates with skills and attributes from diverse areas. In particular, this refers to the mathematic and scientific literacy skills required in engineering which include: problem solving, research and development, and analysis and synthesis skills.

The importance of scientific literacy to engineers is well-established. Of specific note is the final dimension from Laugksch (2000) where the scientific literacy of manipulative skills is identified. This dimension includes the ability to utilise effective visualisation skills. A substantial part of engineering design depends on the development and manipulation of objects and shapes which is generally done as a cognitive process prior to ideation where the ideas are formalised in technical drawings. The ability to understand concepts from drawings and to be able to manipulate these concepts is fundamental to engineering design.

3D Spatial Ability Test

One major objective of the ALTC project is to develop a measurement instrument (3DAT) that will underpin the development of learning tasks to improve visualisation skills. The 3DAT research started with unskilled groups (no prior learning) in a preliminary study consisting of nine subtests and 119 test items. Through item analysis, the 3DAT was reduced to six subtests and 45 test items. This process included a review of correct responses and reaction times and the evaluation of reliability and correlation measures. Later, a web version for unskilled groups was developed and comparisons were made with the earlier laboratory-tested version. Validity and reliability measures were encouraging. Smaller Honours projects investigated predictive, convergent and divergent validity, while others investigated gender differences and the impact of initial 3D learning tasks on spatial ability performance. Procedures and sequencing were deliberate to conform to the standards required for psychometric test development.

The 3DAT is being developed to measure spatial ability as it applies to graphical communication using a range of spatial cognition tasks. 3DAT addresses all the skills emphasised in traditional training, such as understanding of different types of projections, the concept of true length, folding and unfolding and the properties of coordinate systems. The test items are varied in form and are novel in design. In essence, the items are matching, recognition and visualisation tasks requiring varying forms of spatial ability. The final version of the 3DAT will consist of groups of test items called subtests that represent different elements of spatial ability relevant to science and engineering disciplines.

Current Studies

Background

A study was conducted with first year university engineering students and a mixture of other disciplines as a further step in the development of the 3DAT. The study aimed at profiling the spatial ability of two groups (engineering and creative) with an expectation that performance would be better for the engineers. If the 3DAT was being developed for engineers, there needed to be a significant difference in performance favouring engineers. If both groups performed equally well, the 3DAT would not necessarily identify weaknesses unique to science and engineering students. In a psychometric test development domain, this is called predictive validity. An opportunity was also taken in this study to examine differences in gender performance across both groups. The literature constantly refers to gender bias favouring males for visualisation tasks. It was always intended that the finished version of the 3DAT would identify where training was needed to bring about visualisation improvement for poor performers and female students. The study was computer-based and tested 6 spatial subtests consisting of 6 test items each and measured choice accuracy and response time (RT). The subtests were a combination of tasks that researchers wanted to re-test with students having prior learning experience, and tasks that were being trialled for the first time. For tasks previously used, the degree of difficulty was increased. The six subtests were named: mental rotation (MR), visualisation (VZ), dot coordinate (DC), mental cutting (MC), fold unfold (FU) and true length (TL). The subtests were varied in design which would help identify factors of spatial ability if they existed in this research. Two examples of subtests are shown in Figure 1.

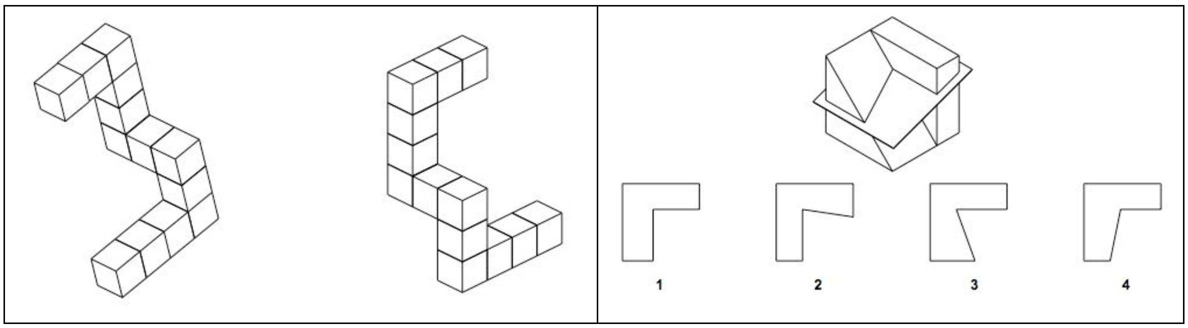

Figure 1. Subtest on the left (MR) requires participants to decide if the images are the same or different (mirror). Subtest on the right (MC) requires participants to decide which option represents the intersection of the plane and the 3D object.

The study had ethics approval to be conducted in normal tutorial classes because of the educational value to participating students. They received a rationale for the study, an explanation of its relevance to their curriculum and the opportunity to calculate their performance overall and for each of the subtests. The sample consisted of 114 participants (68 engineers and 46 creative) and of these 87 were male and 27 were female. The engineers group was made up of students from mechanical, chemical and mechatronics programs while the creative group consisted of students from architecture, construction management and design and technology programs.

This study was the outcome of collaboration between unusual partners (applied psychology and design education). It established a link between these disciplines and demonstrated the application of applied psychology to teaching practice in another discipline. It is an example of cross-discipline cooperation and a model of how applied psychology can work. Potentially, it will show that psychology research and methodologies can lead to good teaching practice in how visualisation is taught in higher education. This partnership continues and provides an opportunity to bring about change in an area that is mostly neglected.

Results

Since there were six test items for each of the six subtests, the maximum score possible on each subtest was six. Figure 2 shows the plot of mean scores for each group of participants. Clearly shown is the consistently better performance for the engineer group. The performance across all subtests was statistically significant ($t\ (112) = 4.37$, $p = .000$) in favour of engineers. However, when each subtest is considered individually, only DC and MR task are significant ($t\ (112) = 7.47$, $p = .000$ and $t\ (112) = 2.52$, $p = .013$ respectively) with VZ trending towards significance. Most notable was the subtest DC with an effect size (practical significance) of 1.4 which is well above the criteria for large effect (low = 0.2, medium = 0.4, large = 0.8). In comparison, effect size for MR was 0.47 and for VZ, it was 0.30. A review of the remaining subtests (MC, FU and TL) indicated that many test items failed to discriminate and were near ceiling for degree of difficulty. However, the results are encouraging since they support the hypothesis that engineers will do better on tasks that target their spatial attributes. In other words, the results go some way towards establishing predictive validity which is a requirement of psychometric test development.

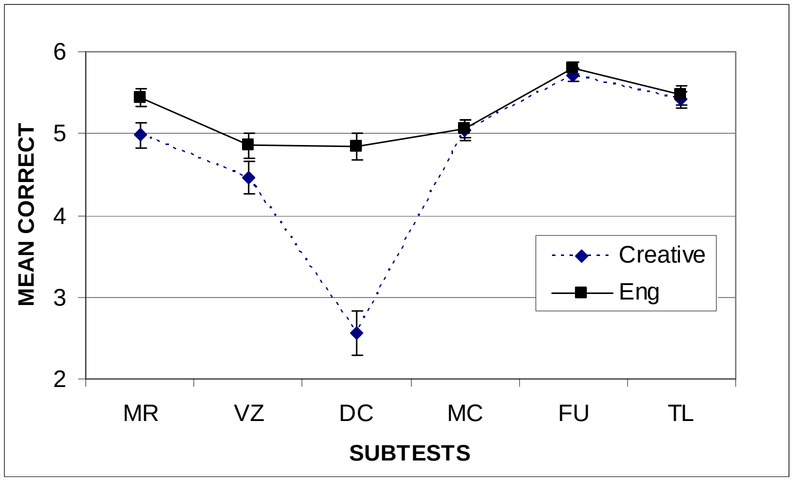

Figure 2. Plot of mean correct and standard error on visualisation tasks for engineering and other participants

The plot in Figure 3 shows mean correct scores for male and female participants across the total sample. Female performance is consistently below that of males on all subtests reaching statistical significance on all subtests except TL. Accordingly, statistical significance can be reported across subtests when considered collectively ($t (112) = 4.74$, $p = .000$). Noteworthy again is subtest DC with a high effect size of 0.99. Unfortunately, these results support the literature that provides evidence of gender bias favouring males. Ideally, it would be good to be reporting a trend in the opposite direction where females were moving closer to the performance levels of males on visualisation tasks. However, the sample size for females was small in comparison which may have some implications for these findings.

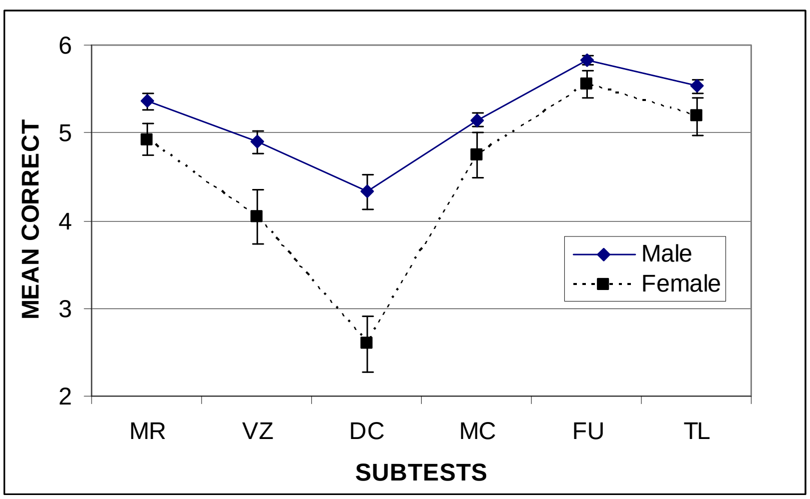

Figure 3. Plot of mean correct and standard error on visualisation tasks for male and female participants

A Case for the Dot Coordinate Subtest

The need for certain science disciplines to have an appreciation of spatial abilities is important. Although there is potential for further study in this domain, there is reason to believe that the abilities related to the DC subtest would have direct application in some of the sciences. A significant part of the physical sciences relies on understanding micro, and now nano, attributes of structures. At this level, understanding the dimensional properties and the physical proportions and relationships of components is only able to be achieved initially at the cognitive level. At this point it is able to be documented. To achieve this level of understanding, spatial ability is important. As for engineers, scientists rely on mental imagery to understand or create new knowledge. Thus, the need for spatial abilities should then be important to scientists. As for engineering, science needs to consider strategies to improve students' spatial abilities as well as a range of other core skills within their respective curricula.

Conclusion

Exploratory factor analysis failed to identify any specific factors of spatial ability often reported in the literature. However, subtests TL and DC trended this way with encouraging correlations. Part of the problem may have come from easy test items for some subtests that did not discriminate at an acceptable level. The study also reported gender bias in keeping with the literature with males consistently performing better on all subtests. Importantly, engineers as a group performed better on all subtests and statistical significance was achieved for two subtests and trended this way for a third. Science understanding is considered fundamental to engineers but less so for the disciplines in the second group. The 3DAT is being developed to identify poor performers in the disciplines of science and engineering and results of this study indicate that the 3DAT is moving in the right direction. Results provide evidence of predictive validity which is a standard requirement for any psychometric test development.

The next stage in developing the 3DAT is to test an additional range of subtests and increase the difficulty level of some promising subtests. After this, the 3DAT will move to online development. This will open the 3DAT to a far larger cohort with the hope of identifying weaknesses to allow teaching staff to improve training methodologies for an important but often neglected area. To many, visualisation is the key to conceptual development and regarded as a core communication skill for both engineering and science disciplines.

References

Adanez, G.P. and Velasco, A.D. (2002) Predicting academic success of engineering students in technical drawing from visualization test scores. *Journal of Geometry and Graphics*, **6**(1), 99.

Allahyar, M. and Hunt, E. (2003) The assessment of spatial orientation using virtual reality techniques. *International Journal of Testing*, **3**(3), 263–275.

Maier, P.H. (1998) Spatial geometry and spatial ability: How to make solid geometry solid? In E. Cohors-Fresenborg, K. Reiss, G. Toener and H.-G Weigand (Eds), Selected papers from the Annual Conference of Didactics of Mathematics 1996, Osnabreck, 63–75.

Nguyen, D. (1998) The Essential Skills and Attributes of an Engineer: A Comparative Study of Academis, Industry Personnel and Engineering Students, *Global Journal of Engineering Education*, **2**(1).

Laugksch, R.C. (2000) Scientific Literacy: A Conceptual Overview, Science Education, Wiley and Sons, **84**, 71–94.

Sorby, S. (2006) Developing 3-D spatial skills for engineering students. Paper presented at the Australasian Association of Engineering Education Conference, Auckland University of Technology, New Zealand.

Sutton, K.J. and Williams, A.P. (2007) Spatial Cognition and its Implications for Design. *International Association of Societies of Design Research*, Hong Kong, China.

Sutton, K., Heathcote, A. and Bore, M. (2005) Implementing a web-based measurement of 3D understanding. Australian Computer-Human Interaction Special Interest Group Conference Canberra, Australia 2005.