Research outcomes supporting learning in spatial ability

Ken Sutton
The University of Newcastle, Callaghan NSW Australia
Ken.Sutton@newcastle.edu.au

Anthony Williams
The University of Newcastle, Callaghan NSW Australia
Tony.Williams@newcastle.edu.au

***Abstract**: This paper reports on studies (Pollock 2006, Day 2006) that examined performance on a range of spatial cognition tasks considered important to designers. It provides evidence that helps validate a new psychometric test developed to measure spatial concepts represented in graphical communication. The test was developed to analyse the performance of novice designers on tasks requiring a range of spatial reasoning skills.*

Also reported is work in progress which focuses on designing and developing computer learning tasks to improve spatial ability relevant to design. We discuss the traditional approach which is based on observation, demonstrations and the use of plastic models to explain actual 3D concepts. We outline research that points to active exploration as a better alternative and discuss the application of modern software to produce interactive computer models guided by this research. We advocate moving from the traditional approach of learning to active learning using interactive computer models that allow user-controlled manipulation.

Introduction

When we confront an object for the first time our natural response is to rotate it and to try and come to an understanding of its form and physical properties by considering it from a number of perspectives. If it is too big to manipulate manually then it is not beyond our imagination to walk around it to gain a multiple perspective understanding of the object. In the physical form this is possible but for much of the process of design, no solid object exists. Therefore the process of the design of physical objects is done initially in the mind and then committed to paper or screen prior to the realisation of the objects solid form.

This paper looks at the issue of spatial ability which provides us with the capacity to do the mental manipulation of designs or to appreciate the relationship of components of these forms. There is considerable debate about the “state” of these spatial skills and questions raised include:

- Are they innate?
- Is it possible to teach them?
- Is spatial ability a set of skills rather than just one skill?
- To what extent do variations in the skill set exist?
- Do these skills impact on a designer’s capacity to design?

As we begin to understand these skills more fully, answers to these questions will be developed. This paper reports on initial research which considers spatial ability and its implications for design and the preparation of the next generation of designers.

What is spatial ability

In many design fields there is a level of graphical communication utilised in ideation of design concepts, communication of concepts or the documentation of designs. As such graphical communication and computer assisted design (CAD) are fundamental components of Design courses. What has been noted in recent years is the amount of preparation students have in these skills at entry to University. One of the more important aptitudes for students studying design or graphical related topics in engineering is spatial ability. Spatial ability can be defined as the performance on tasks that require:

- mental rotation of objects,
- the ability to understand how objects appear at different angles, and
- how objects relate to each other in space.

Graphical communication is used extensively in the design domain by engineers, architects and other design-based disciplines. These techniques are utilised to share design and technical information about objects such as buildings, machinery, products and structures. To effectively participate in these activities designers must utilise their spatial abilities.

An important domain of spatial ability is “3D understanding”. 3D understanding is considered as the ability to extract information about 3D properties from two-dimensional (2D) representations (Sutton, Heathcote, & Bore, 2005). This skill set consists of the visual and perceptual abilities required to interpret what is seen, and spatial abilities to mentally manipulate visual representations. Design students require this ability when thinking and reasoning in 3D by drawing conclusions from a set of 2D drawings based on a notational system. The importance of the ability to work effectively with graphical communications is stated by Salthouse (1991) who asserts that engineers are professionally incompetent if they are deficient in their ability to understand graphical communications.

Why is spatial ability important

There is a body of research that indicates the importance of spatial ability in graphics-based courses and the implication of poor skills on success rates and career choices. Research also points to gender differences in favour of males and that the development of spatial ability is best implemented prior to tertiary education. Some of this research is reported below.

In many of the design fields, including engineering, there is a level of graphical communication utilised in both communication of concepts and documentation of designs. As such graphical communication or CAD is a core component of many of these courses. Due to changes in the secondary school curricula, students are entering university with less drawing skill development and experience than those of past generations. The imperative to prepare students with these skills is now placed on the design programs offered by universities (Sutton and Williams 2006).

Blasko, Holliday-Darr, Mace & Blasko-Drabik (2004) report a concern, identified in their study at Penn State Erie College about low grades and high dropout rates within engineering programs. Despite high achievement at secondary level, students demonstrated deficiencies in basic spatial ability. Blasko and Holliday-Darr (1999) tested incoming engineering students on a number of variables believed to influence retention rates and achievement in first year engineering courses. These variables included educational background, motivation, verbal reasoning and spatial ability. Their findings identified that a strong predictor of success in first year engineering was performance on basic spatial ability tasks.

Sorby (2006) reported that 3D spatial skills have a direct correlation to success in a variety of careers including engineering and science. At a time when visualization skills are increasingly important to engineering students, engineering graphics (the primary course where students first learn visualization concepts) receives less emphasis, in many cases, dropped from the engineering curriculum. Sorby provides evidence of the successful outcome achieved by a bridging course aimed at improving prerequisite 3D spatial skills needed to succeed in graphics courses. Both Sorby and Blasko et al. (2004) identify a gender bias against females in spatial performance.

Success in graphics courses requiring spatial ability skill is routinely cited as having negative consequences leading to under performance. Adanez (2002) suggests that difficulty coping with graphics based courses lead to poor academic performance which in turn contributes to not continuing with their studies. Potter & van de Merwe (2001) support to this position identifying spatial ability and visual imagery have an influence on academic performance in engineering. They highlight high failure rates among engineering students across several universities and relate the importance of early detection of students with difficulties. In particular, Potter & van der Merwe maintain that a student's level of spatial ability at the time of intake to university is an important factor in their overall academic performance. They suggest that there would be value in appropriate graphics courses being offered at secondary school level. They have a strong belief that improvement in spatial ability is possible with appropriate intervention prior to participation in university level graphics courses. They report that students vary in spatial ability and those with low scores are at a higher risk of failing engineering graphics courses. Since the tertiary sector does not have a strong influence over secondary education, it becomes more critical for the sector to have a direct focus on improving spatial ability in its first year graphical communication courses. Also, training has the potential to develop spatial skills with particular benefits for low performers. Lajoie (2003) goes further and states that there is evidence in aptitude research to support the concept that low ability learners gain more from training than high ability individuals. Interestingly, Lajoie suggests that training on some spatial tasks show greater levels of improvement for women than for men who undertake the same training.

Strong & Smith (2001) indicate that spatial visualization (a domain of spatial ability) is recognised as a predictor of success in several technology related disciplines. They consider spatial visualisation skill levels coupled with changes in technology to be an argument for more attention to curricula and teaching which focuses on spatial cognition. The authors also contend that it is the type and length of experiences that have the greater impact on spatial ability and may compensate for other factors like age and gender. Of special importance to this paper is a strong observation from Strong & Smith. They comment that there are many spatial ability tests in existence, but the fact is that many previous studies have been limited in size and scope with variances in testing methods that question the validity of these studies.

How has it been taught to date

The conventional approach to teaching spatial ability is partly passive (Sutton, Heathcote & Bore, in press). In this sense, *passive* refers to the actual learning of 3D concepts though sketching is often used to demonstrate and reinforce what has been learnt. Participants learn from observing instructor-based demonstrations that primarily focus on scaled models of objects encased in plastic frames (Duesbury & O'Neil, 1996). Often the views of an object are manually projected onto planes represented by the plastic frames to illustrate what is seen from different viewing directions, and to demonstrate what changes occur when an object is moved. Such learning techniques provide very little hands-on experience and encourage students to rote-learn a set of rules rather than developing a deeper understanding. Rote learning can be effective for simple and familiar examples but is unreliable for complicated and novel structures (Sutton et al. in press).

Most design students receive very little formal training in the skills of spatial manipulation. Instead, it is generally left to their natural ability, or ad hoc experiences, (sometimes as graduates) to attain these skills. However, engineering programs often include drawing in the first year of study since it is regarded as a core skill needed by students for subsequent subjects in their program. This is where specific efforts to improve spatial ability should occur.

The teaching of drawing skills often involves drawing processes where 3D drawings are redrawn as 2D drawings (orthogonal projections), or a set of 2D views are redrawn into a single 3D view (isometric). There is often no skill development in the transfer of concept images to formal drawing forms or even the documentation of real objects. Drawing is often taught in a procedural manner rather than through the deeper learning processes which encourage a diversity of approaches to learning. In many cases, the learning is somewhat incidental rather than deliberate.

Developing a measure of 3D ability

Two studies, conducted at the University of Newcastle (Pollock 2006, Day 2006), assessed the validity of a psychometric test of 3D understanding under development and compared spatial abilities of two groups of participants described as unskilled and skilled. These studies were concerned with one form of validity assessment known as predictive validity where skilled participants are expected to perform better than unskilled participants. Otherwise, the test would not be achieving its intended purpose. The psychometric test is known as the 3D Spatial Ability Test (3DAT) and was developed as a measure of 3D understanding relevant to novice designers in a graphical communication context. The unskilled group of participants (university psychology students) were those with no prior graphical communication experience, while the skilled group were those with prior graphical communication experience (novice designers).

The studies were conducted under laboratory conditions and in accordance with established psychological methodology protocols and data were analysed using standard and appropriate statistical procedures. The studies used the 3DAT which is a computerised test consisting of six subtests representing different forms of spatial ability and it measures both accuracy and response time. The underlying hypothesis is that no one spatial task is ideal to measure spatial performance of designers. Instead, to gain a measure of their understanding, multiple subtests are considered appropriate. Also used was a range of paper ability tests that each measured accuracy on a set of test items within a set time frame. The studies assessed the validity and reliability of the 3DAT by comparing performance of the unskilled and skilled groups on both the 3DAT and the paper ability tests. Only results on the 3DAT are reported here.

The 3DAT is delivered on a computer using psychological experimental research software (SuperLab Pro) and consists of 45 items divided into six subtests, three of which are two-way. Five subtests are based on previous psychological research including the correct fold and mental rotation tasks used by Blasko et al. (2004). The sixth subtest is based on the idea of true length, an important concept in graphical communication (Sutton et al. in press). An edge of an object can be represented in any view of the object but its true length is not always seen. Only edges parallel to a projection plane have their true length in a projection. The items are varied in form and novel in design and are constituted of straight lines and flat planes. They were created using a CAD package (AutoCAD) and saved in bitmap format to suit the experimental software. Following is a description of each of the six subtests:

- 2D3D Recognition: Objects are presented as orthographic and isometric projections. Participants select which of two alternatives of one type match a standard of the other type (Cooper, 1990; Bertoline & Miller, 1990). Subtests use either (A) an orthographic standard or (B) an isometric standard.
- Correct Fold: Objects are presented as an isometric projection or as an unfolded view. Participants selected which of two alternatives of one type matched a standard of the other type (cf. Blasko et al. 2004). Subtests use either (A) an isometric standard or (B) an unfolded standard.
- True Length Recognition: Objects are presented as isometric and orthographic projections (Sutton et al. in press). In one subtest, participants decide which view in a set of orthographic projections shows the true length of a labelled edge in an isometric projection (True Length Recognition A). In a second subtest, participants decide which of three isometric projections shows the true length of a labelled edge in a set of orthographic projections (True length Recognition B).
- Mental Rotation: Participants decide if a rotated isometric projection of an object matches the isometric projection of a standard or its mirror image (Metzler & Shepard, 1988). The object on the left is always in the same position and is the referent. The object on the right can be the same or the mirror image of the referent and its orientation in the XY plane can be different.
- Object Decision: Participants decide if an isometric projection can represent a 3D object (Schacter & Cooper, 1990). The objects can be one of two types. The first (possible) is one where the projection can reasonably represent a true object. The second (impossible) displays some visual feature that could not reasonably represent an aspect of a true object.
- Dot Coordinate: Participants are shown an isometric projection of a 3D Cartesian coordinate system and a text description of the position of a point in that system (Bore & Munro, 2002). From four orthogonal projections, participants choose the projection that corresponds to the description.

Results of studies

Standard statistical analyses were applied to the results of the two studies (Pollock 2006, Day 2006) to determine descriptive statistics, means and correlation values. Generally, the scores for both the skilled and unskilled group produced acceptable alpha reliability coefficients (0.6 to 0.9). Psychometric standards define acceptable coefficients as greater than 0.7 with values above 0.8 considered highly acceptable. Values closer to zero indicate poor consistency across items. These results provide an overview of the consistency of test items in the 3DAT.

Shown in Figure 1 are performance scores in terms of mean percentage correct for each subtest of the 3DAT for both skilled and unskilled groups. Noteworthy is that the skilled group consistently performed better than the unskilled group on all tasks with some results approaching 100%. These results help establish the validity of the 3DAT for designers since skilled participants are expected to perform better than unskilled participants (predictive validity). However, there are issues for novice designers. Better than expected results are shown for 2D3D recognition and True Length recognition subtests which focus on the ability to think in 3D but work in 2D, or conversely, to think in 2D and decide about 3D properties. This suggests novice designers are more advanced in these skills than generally thought. These subtests are representative of fundamental skills for designers. Conversely, results for the Dot Coordinate subtest do not achieve such levels of success. This subtest requires substantial mental manipulation and visualization on the part of the participants, interestingly it is also considered a fundamental skill for designers when dealing with ill defined concepts. Of special note is the poor performance of the unskilled group (36% correct) which is marginally better than chance level (25%) for this particular subtest given the number of answer alternatives. Though the skilled group performed better (60%), simply guessing is a possible factor in these results. Overall, these results indicate an issue for design education and graphical communication courses developed for engineers and designers.

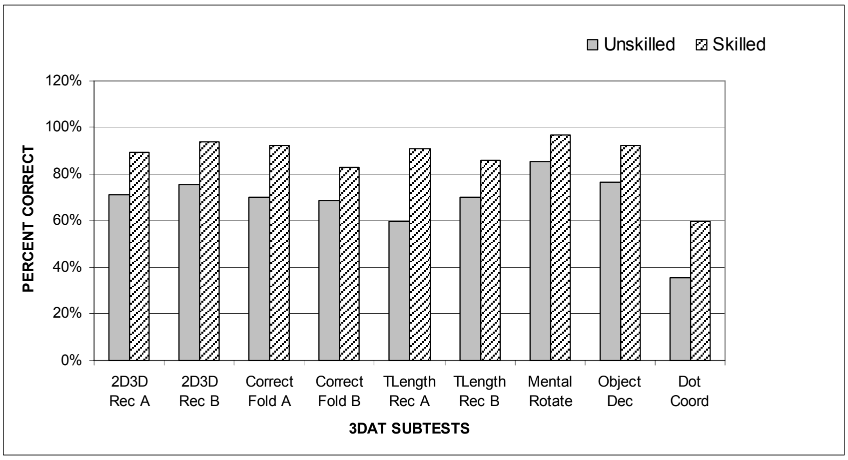

Figure 1: Comparison of 3DAT Subtest Scores Between Skilled and Unskilled Groups.

Implications for engineering education

The 3DAT revealed that tasks requiring advanced spatial and visualization skills were not handled well by many novice learners. These tasks involved a number of complex mental manipulations to demonstrate a clear interpretation of the given task. Importantly, these tasks reflect the type of understanding a designer would be expected to have. The results suggest that learning activities in graphical communication courses designed to improve higher spatial thinking should be given greater emphasis. 3D learning tasks that allow active exploration will help in this regard.

The 3DAT also highlighted that tasks typical of basic 3D concepts required by designers are better understood than generally assumed. These tasks were essentially about identifying a 3D object from a set of 2D drawings, or conversely, recognising which set of 2D drawings represented an object presented in 3D format. Some of these tasks dealt with the important concept of true length of edges where two flat surfaces meet. The findings imply that principles related to 2D-3D recognition are better understood than generally thought. The implication is that time normally spent on learning activities of this nature could be reduced. Also implied is that first-time students may have a more advanced starting point than generally appreciated. This may mean a better foundation for more complicated concepts and a speedier progression for students studying design.

The studies' findings provide an insight into the problems experienced by novice designers with spatial ability tasks. This could serve to underpin the development of learning tasks to improve spatial ability. The advantages of active exploration to improve 3D understanding concepts should be considered. Evidence strongly favours learning by doing (experiential learning) and the software now exists to develop simulated, interactive and animated learning tasks that allow student-based learning. Many design educators will see the advantages of tasks that have these attributes.

An alternative to passive learning of 3D concepts is described as active learning. Active learning, in this context, encourages discovery through interactivity, object manipulation and animation controlled by the learner. Researchers (e.g., Harman, Humphrey & Goodale, 1999 (as cited in James, Humphrey, & Goodale, 2001), James et al. 2001) report that learners who have active control over novel objects perform better on later tests of object recognition and mental rotation. Further evidence (e.g., James, Humphrey, Viles, Corrie, Baddour, & Goodale, 2002; James, Humphrey, & Goodale, 2001) suggests that active exploration and control of novel objects assists the learning of 3D structures, better object recognition and improved spatial ability. Other researchers including Gibson (1979) and Neisser (1976) (as cited in James et al. 2001) have emphasized the importance of motor activity, including exploratory activity, in perceptual and cognitive development. Similarly, James et al. (2001) provide evidence "that active exploration of novel objects leads to better performance on later tests of object recognition." (p. 118). In a different setup, James, et al (2002) conducted studies in a virtual reality environment and their results also indicate that allowing active exploration of an object during initial learning can facilitate recognition of that object, perhaps owing to the control that the participant has over the object views upon which they can focus. In a study that examined the perceptual skills of maintenance technicians who must learn to visualise mechanical systems, Johns & Brander (1997) argue that perceptual skills may be improved in a practice environment where a learner is able to actively explore, interact, manipulate and control 3D animations and simulations. They considered that maintenance technicians required advanced spatial skills to visualise complex relationships between components and to visualise mechanical problems and practical solutions. They also believed that multimedia computer-based training (CBT) techniques using 3D animations offered significant advantages over traditional mechanical skills training. Traditional training of mechanical skills are based on demonstrations, workshop exercises and on-the-job training. Duesbury & O'Neill (1996) conducted a study that examined the effects of practice in a 3D CAD environment on a learner's ability to visualise objects represented by multi-view drawings such as blueprints. Their study consisted of two treatment groups (rotational and non-rotational) and one control group. They found that the rotational treatment group performed significantly better than both the non-rotational and control groups on tests of spatial ability and 3D visualisation ability. They concluded that spatial ability can be improved through practice where the learner is able to see the relationship between the 2D and 3D characteristics of an object. In another study, Bertoline (1990) questioned the relevance of traditional teaching of graphical communication in a modern engineering graphics environment. The author makes a case for taking advantage of modern software and computer technology to achieve better results.

What these findings have in common is that they argue in favour of active exploration over passive observation to improve spatial ability. Even though there is a collection of research and educational thinking that underlines the value of learning by doing, James et al. (2001) point out that "this idea has not often been applied to perceptual learning in vision." (p. 118). The research reported here provided the impetus to develop the interactive 3D computer-based learning tasks to improve spatial ability reported below.

Works in progress

Advanced 3D graphics and multimedia software make it possible to produce 3D models that allow active exploration and learner-controlled manipulation of realistic objects. Whilst the software itself requires some dedication to master the features required to produce interactive 3D learning tasks, a distinct advantage, however, is that it also allows executable files to be created to produce stand alone applications independent of the parent software. This gives control to developers to exclude all but the very basic skills required by learners to use the learning tasks.

To achieve the computer imagery required, a graphics package (3Ds Max) capable of producing realistic 3D models, and a multimedia package (MX 2004 Director) able to handle 3D models are being used. Director is especially ideal because of the high standard of interactivity it allows. Collectively, the software provides user-controlled, interactive and rendered 3D models where animation and real-time simulations are possible. The result is a range of learning tasks that can be manipulated, controlled and explored. The activities are considered parallel to handling real objects and examining them by touching, exploring, manipulating and dismantling. The learning tasks offer users the flexibility to work at their own pace and opportunities to explore objects. Users are able to move and manipulate objects to test concepts and understanding. Some resistance to this form of development is possible because of the financial costs involved, but this argument is difficult to follow. In view of the potential for widespread dissemination and the ease at which the tasks can be modified, the cost overall is justified. The tasks would serve well as a supplement to other strategies used by design educators to improve spatial skills.

There are 10 activities with graded exercises in each and feedback is provided to assist the learning process. The package also contains a set of self-assessment exercises related to the learning tasks. They are varied and also have feedback and 'try again' options. A brief description of each learning task and the competencies expected to be achieved are outlined below:

- Introduction: Introduces the tools that can be used in the remaining learning tasks that make manipulation and interaction possible.
- Multiple Views: Manipulation of a 3D object that shows changes in 2D views. The aim to show the relationship between the position of a 3D object and its 2D views.
- Mental Rotation: Compares 3D objects where one object is fixed and the other can be rotated. Manipulation allows decisions about whether the objects are the same or different.
- Water Level: Decisions about water levels when a container is rotated from the upright position.
- Intersecting Solids: Movement of 3D objects so that they intersect at various angles. The purpose is to show the lines of intersection when the objects touch each other in any number of positions.
- Dot Coordinate: Allows manipulation of an object in space about the X, Y and Z axes to satisfy a given set of coordinates. Decisions about correct 2D views are also required..
- Viewing Directions: Compares 3D objects with line drawings through rotation and close inspection to decide if visual violations exist.
- Correct Fold: Allows control of animation that shows the result of folding and unfolding the surfaces of a 3D object.
- True Length: Rotation of 3D objects into positions to identify the viewing direction necessary to see the differences between true length of an edge and its apparent length.
- Section Planes: Permits movement of several lines representing cutting planes through a 3D object. Produces a variety of planes to assist determine the correct 2D view from a given set.

Conclusion

This paper provided an overview of spatial ability and outlined its importance to novice designers. It spoke of the low attention given to improving spatial ability and the implications for design education and design creativity. The types of tests typically used to measure spatial ability were described and the development of a 3D ability test specifically to assess the performance of designers was discussed. Findings from one application of the 3D ability test were examined and approaches to improving spatial ability based on research favouring active exploration were advocated.

This paper also reported work in progress that focuses on computer-based learning tasks that allow user-controlled interactivity and manipulation to improve spatial ability. We provided an overview of traditional learning to teaching 3D concepts centred mostly on observation and instructor-led demonstrations. As a better alternative, we promoted moving to active exploration and taking advantage of the human-computer interaction that is possible with modern software. Research that demonstrates the importance of active exploration to visual perception and object recognition is reported. Once developed and tested to satisfaction under laboratory conditions, the learning tasks are expected to have an impact on how graphical communication is taught to students at both secondary and tertiary institutions. The learning tasks will be easy for learners to use which is made possible by the advanced software and computer interfaces that are available today.

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