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SPATIAL COGNITION AND ITS IMPLICATIONS FOR DESIGN

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ABSTRACT:

This paper reports on studies conducted at the University of Newcastle (Pollock 2006, Day 2006) that examined performance of participants on a range of spatial cognition tasks considered important to designers. It also provides evidence that helps validate a new psychometric test developed to measure spatial concepts represented in technical drawings. Participants were university students divided into a skilled group and an unskilled group based on whether or not they had prior technical drawing experience. The skilled group did consistently better on spatial ability tasks with differences in performance shown to be statistically significant. Tasks requiring advanced spatial skills associated with coordinate systems were found to be difficult. Other tasks requiring spatial reasoning to identify three-dimensional properties from two-dimensional drawings produced better results than expected. The paper concludes with an overview of implications for designers and technical drawing courses. Results also provide confidence in the psychometric instrument as a reliable measure of spatial ability appropriate to designers.

Keywords: Spatial Ability, Visualization, Design Education.

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 are developed. This paper reports on initial research which considers spatial ability and its implications for design and design educators.

WHAT IS SPATIAL ABILITY

In many design fields there is a level of graphic communication utilised in ideation of design concepts, communication of concepts or the documentation of designs. As such technical drawing and computer assisted design (CAD) are fundamental components of Design courses. What has been noted in recent years is the amount of experience students have in these skills on entry to University. One of the more important aptitudes for students studying Design 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
- how objects relate to each other in space

Technical drawing is a graphical communication method used by designers, architects and engineers to share technical information about objects such as buildings, machinery, products and structures. To effectively participate in these activities designers must utilise their spatial abilities. To better gain an understanding of these skills is to consider the tests which are used to evaluate them and examples of traditional testing are provided below:

- Space Relations: This test requires mental manipulation of three-dimensional (3D) objects in space. It presents a set of drawings of 3D objects each with four unfolded alternatives for participants to choose from. Participants match one unfolded view with the 3D object.
- Mental Rotation: Participants decide if a 3D object can be rotated into a referent. Participants make a speeded decision about whether the objects are the same or different. The task assesses the ability to mentally manipulate.
- Spatial Visualization: Participants match a choice of unfolded views with a 3D object and is similar to Space Relations. Measures the ability to manipulate complex spatial information when several stages are needed to produce the correct solution. This task is often referred to as the paper-folding task.
- Spatial Perception: Also known as the water-level test. Requires participants to identify a horizontal or vertical location. Measures the ability to determine spatial relationships among objects despite distracting information.
- Object Decision: Participants decide if 3D images are representative of real objects or whether some visual violation exists. Choices are between possible and impossible images. Considered a measure of implicit memory which refers to unintentional retrieval of previously acquired information that does not require conscious or explicit recollection of specific previous experiences.
- Mechanical Reasoning: This test presents pictorial mechanical situations with a simply worded question with several alternative answers for participants to choose from.

- Minnesota Board Test: This test measures mental manipulation of 2D shapes. Participants are required to visualise how a number of separate sections will combine to form a single shape.
- Raven's Matrices: This requires matching a choice from four cut-out sections each containing a different single pattern with a larger section showing one repeating pattern.

The last three mentioned tests are not strictly seen as measures of spatial ability but may be considered as nonverbal ability tests that acknowledge forms of spatial concepts. They are often used for aptitude testing and as part of a set of tests for IQ measurement. Considering these tests and what they are trying to measure provides a cursory overview of what spatial ability is about.

A substantial part of spatial ability is 3D understanding. 3D understanding is the ability to extract information about 3D properties from two-dimensional (2D) representations (i.e., drawings) (Sutton, Heathcote, & Bore, 2005). This skill requires visual and perceptual abilities to interpret what is seen, and spatial abilities to mentally manipulate visual representations. Design students require the ability to think and reason in 3D by drawing conclusions from a set of 2D drawings based on a notational system. The importance of being able to work effectively from technical drawings is probably well demonstrated by Salthouse (1991) who asserts that engineers are professionally incompetent if they are deficient in their ability to understand technical drawings.

WHY IS IT IMPORTANT

There is a body of research that indicates the importance of spatial ability in graphics courses and that poor skills impact 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.

In many design fields there is a level of graphic communication utilised in both communication of concepts and documentation of designs. As such technical drawing or CAD are core components of many design courses. Because of the changes in the secondary school curricula, students are coming to university with less developed skills in drawing. The imperative is now on the design programs in the university sector to prepare students with these skills (Sutton and Williams 2006).

Blasko, Holliday-Darr, Mace & Blasko-Drabik (2004) report on a concern at Penn State Erie College about low grades and high dropout rates in an engineering programs. Despite high grades at secondary level, students appeared to be deficient in basic spatial ability. Blasko and Holliday-Darr (1999) tested incoming engineering students on a number of variables thought to influence retention rates and achievement in first year engineering courses such as educational background, motivation, verbal reasoning and spatial ability. They found that a strong predictor of success was performance on basic spatial cognition tasks.

Sorby (2006) reports evidence that 3D spatial skills are critical to success in a variety of careers including engineering and science which would extend to a range of design courses. 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, and in many cases, has been dropped from the engineering curriculum. Sorby provides evidence of success with a bridging course aimed at improving prerequisite 3D spatial skills needed by students to succeed in graphics courses. Both Sorby and Blasko et al. (2004) comment on gender bias against females for spatial performance.

Other researchers add weight to the concerns of Sorby (2006) and Blasko et al. (2004). The importance of spatial ability to success in graphics courses is routinely cited with some evidence of negative consequences for under performers. Adanez (2002) suggests that coping difficulties lead to poor academic performance which in turn is a reason for not continuing with studies. Potter & van de Merwe (2001) add support to this position and point out that their own research demonstrates spatial ability and visual imagery have an influence on academic performance in engineering. They also provide data to highlight high failure rates among engineering students across several universities and argue the importance of early detection of students with difficulties. In particular, Potter & van der Merwe maintain that the level of spatial ability at the time of intake to university is an important factor in academic performance. They suggest the value of courses at school level and argue that improvement is possible with appropriate intervention. They summarise their findings and report that students vary in spatial ability and those with low scores are at risk of failing engineering graphics courses. They add that training is possible to develop spatial skills with particular benefits to low performers. Lajoie (2003) goes further and states that there is evidence in aptitude research to support the idea that low ability participants gain more from training than high ability individuals. Interestingly, they suggest that training on some spatial tasks show better improvement for women than for men. On another front, Strong & Smith (2001) indicate that spatial visualization is recognised as a predictor of success in several technology related disciplines. They consider this and changes in technology to be arguments for more attention to teaching that 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 note to this paper is a strong recommendation from Strong & Smith. They consider that there are many spatial ability tests in existence and comment that many previous studies have been limited in size and scope with variances in testing methods that further challenge the validity of these studies.

HOW HAS IT BEEN TAUGHT TO DATE

The conventional approach to teaching spatial ability is passive (Sutton, Heathcote & Bore, in press). 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. Passive 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 (sometimes as graduates) to develop 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.

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.

REPORTED STUDIES

Two studies were conducted at the University of Newcastle (Pollock 2006, Day 2006) to assess the validity of a psychometric test of 3D understanding under development and to compare spatial abilities of two groups of participants described as *unskilled* and *skilled*. 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 technical drawing context. The *unskilled* group of participants were those with no prior learning in technical drawing (university psychology students) while the *skilled* group were those with prior technical drawing 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. 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. The 3DAT and paper ability tests are described below.

3D ABILITY TEST (3DAT)

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 technical drawing (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. A description of each of the six subtests follows.

<u>2D3D Recognition</u>: 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. (See example Appendix 1.)

<u>Correct Fold</u>: 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. (See example Appendix 1.)

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). (See example Appendix 1.)

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. (See example Appendix 1.)

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. (See example Appendix 1.)

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. (See example Appendix 1.)

The 3DAT takes about 30 minutes to administer. Each test item requires a speedy response by the participant by pressing a dedicated button on a timing device known as a response pad. The display of each test item is automatic after a selection is made but expires after a set time limit and moves to the next item if no selection is made.

PAPER ABILITY TESTS

Part of developing a new psychometric test is to benchmark it against established tests that measure overlapping abilities such as some nonverbal measures (convergent construct validity), against tests of hypothesized non-overlapping abilities such as verbal reasoning (divergent construct validity), and to test it with a group of participants expected to perform well because of their prior learning experiences (predictive validity with known groups). This study investigated both construct and predictive validity which are standard procedures for psychometric test development.

The tests that were used measured space relations, nonverbal reasoning, verbal reasoning, numerical reasoning and mechanical reasoning. While the 3DAT measures a wider range of abilities, parallels with established measures of spatial ability should exist. It was hypothesized that the 3DAT would correlate with measures of space relations, nonverbal reasoning and mechanical reasoning. It was also expected that correlations would be higher for participants with prior learning in technical drawing (*skilled* group). On the other hand, correlations of the 3DAT with measures of verbal reasoning or numerical reasoning were not expected for either group. The paper ability tests used in these studies are described below.

Verbal Reasoning: This test measures the ability to understand whether the conclusion drawn from certain statements is correct or incorrect. Although the statements are really nonsense and not necessarily logical, the given test items measure a form of verbal reasoning.

Numerical Reasoning: In this test, a set of numerical problems need to be solved based on reasoning. The test is not the same as numerical ability test. Test items are simple statements that require mathematical logic rather than mathematical ability. Most can be done mentally though a calculator can be used. Participants choose from four options.

Mechanical Reasoning: This test presents pictorial mechanical situations linked to a simply worded question with several options for participants to choose from. The test items are typically concerned with rotation, pulleys, levers and loads.

Space Relations: This test requires the mental manipulation of 3D objects in space. Each test item presents an unfolded view of an object and drawings of four optional 3D objects for participants to choose from. Participants match the unfolded view with one 3D object.

Minnesota Test: This test measures mental manipulation of 2D shapes. Participants are required to visualise how a number of separate sections will combine to form a single shape. There are five options to choose from.

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. Though not the focus of this paper, reliability for the 3DAT was also tested by comparing reliability coefficients. 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%. Better than expected results are shown for 2D3D recognition and True Length recognition subtests which particularly 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 thought necessary for designers. On the other hand, results for the Dot Coordinate subtest are not very encouraging. This subtest requires substantial mental manipulation and visualization and is also considered a fundamental skill for designers when dealing with design 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 technical drawing courses developed for designers.

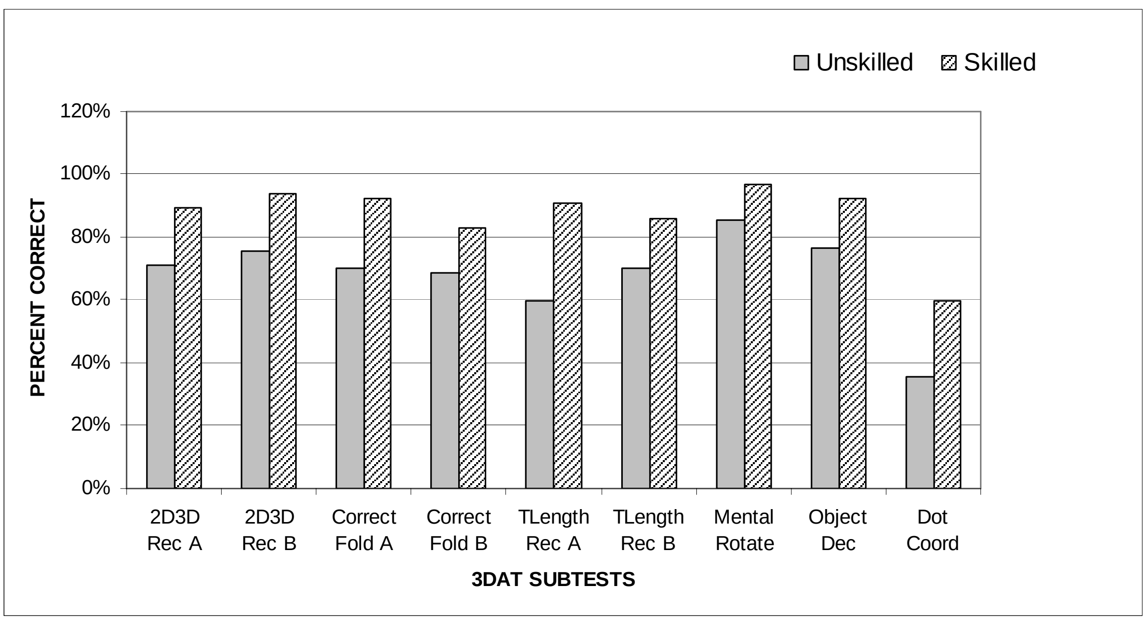

Figure 1: Comparison of 3DAT Subtest Scores (mean percentage correct) Between Skilled and Unskilled Groups.

A similar comparison is provided for the paper ability tests. Shown in Figure 2 are performance scores for both *skilled* and *unskilled* groups. Again, the *skilled* group performed consistently better than the *unskilled* group and particularly on the subtests most relevant to this paper.

That is, the spatial, minnesota and mechanical tests in that order. The results overall are meaningful to the validation of the 3DAT which provides confidence in the instrument as a reliable measure of spatial ability for novice designers. The performance of the two groups on the verbal and numerical reasoning tests could be a focus of a future study though statistically the difference is not significant despite the appearance of the results on the chart. Figure 2 is a graphical representation of a more detailed analysis provided later in this paper.

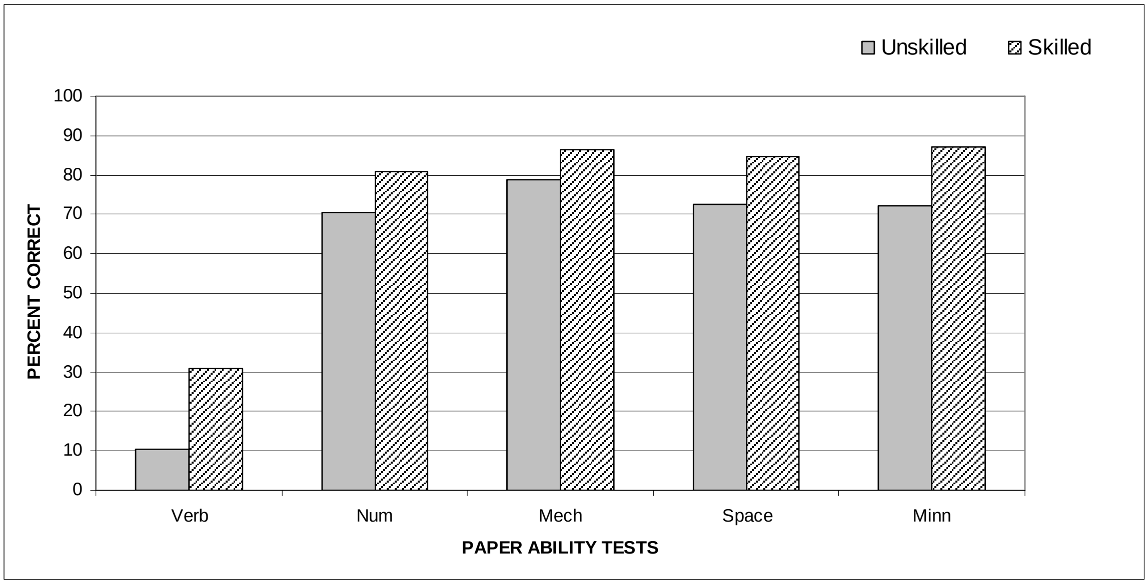

Figure 2: Comparison of Paper Ability Tests (mean percentage correct) Between Skilled and Unskilled Groups.

Shown in Table 1 are correlation values for the 3DAT and the space relations paper ability test with significance values shown. Values indicate the strength of the relationship between the tests and correlation is significant at the 0.05 level or less. These results provide further confidence in the 3DAT since it correlates significantly with an established test of overlapping abilities. This is a standard validation requirement for any test development. Importantly, the *skilled* group who were novice designers performed consistently on both tests.

Skilled Group	Measure	Space
3DAT	Correlation	.634
	Significance	.020
Unskilled Group		
3DAT	Correlation	.792
	Significance	.000

Table 1: Correlation Values for the 3DAT and Space Relations Test for Skilled and Unskilled Groups.

Descriptive statistics for the studies are provided in Table 2. Also shown are significance values after comparing means using a standard statistical procedure (t-test). Significance values equal to 0.05 or less indicate that differences are statistically significant. Thus, from these results, it can be seen that the *skilled* group performed better than the *unskilled* group on the 3DAT and the space relations test which are those that are most important to novice designers. It would be a concern if the differences were not significant because either the tests were not measuring what they purport to measure, or the novice designers did not possess spatial skills superior to groups identified as not having prior learning in design-related experiences. Though less of a measure of spatial ability, the mechanical reasoning test shows a significance value approaching 0.05 which is also encouraging. Most design educators would like to think that novice designers are superior to unskilled groups in this important ability. Of interest is the significance values for the verbal and numerical reasoning tests. Values indicate that the difference in performance between the two groups is not significant and this reflects favourably on the 3DAT since it further validates its relevance as a measure of spatial ability for designers. For the 3DAT to be a reliable instrument, there should not be a significant difference between the two groups because these tests are examples of tests of non-overlapping spatial abilities with the 3DAT. In other words, there is an expectation that both groups under normal circumstances would perform about the same on measures of abilities other than spatial.

Test	Group	N	Mean	StdDev	Sig
3Dat	Skilled	13	87.18	10.47	.000
	Unskilled	18	68.15	13.61	
Verb	Skilled	13	30.77	34.16	.099
	Unskilled	18	10.37	31.87	
Num	Skilled	13	80.77	22.40	.346
	Unskilled	18	70.37	34.09	
Mech	Skilled	13	86.59	10.84	.095
	Unskilled	18	78.73	13.59	
Spac	Skilled	13	84.87	11.35	.021
	Unskilled	18	72.69	15.24	
Nonverb	Skilled	13	87.14	10.47	.004
	Unskilled	18	72.22	14.38	

Table 2: Descriptive Statistics for Skilled and Unskilled Groups with Significance Values for Differences Indicated.

IMPLICATIONS FOR DESIGN 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, especially for any project of reasonable complexity. The results suggest that learning activities in technical drawing 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.

One of the benefits of the reported studies is that the 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 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.

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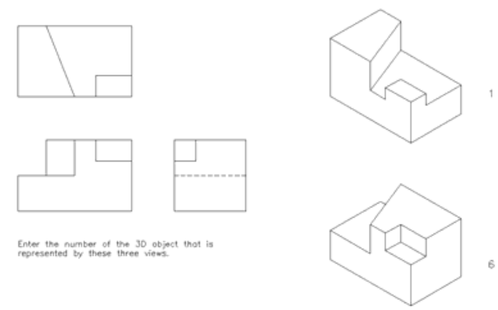
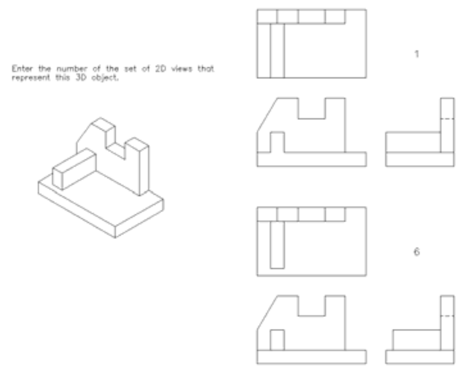
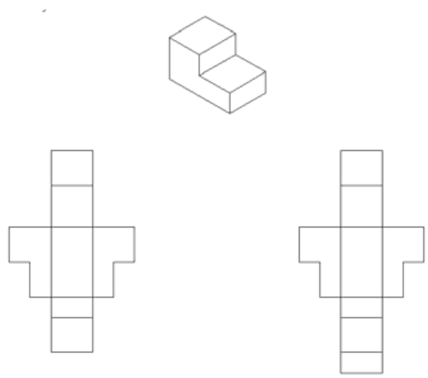
APPENDIX 1: EXAMPLES OF 3DAT SUBTESTS TASKS

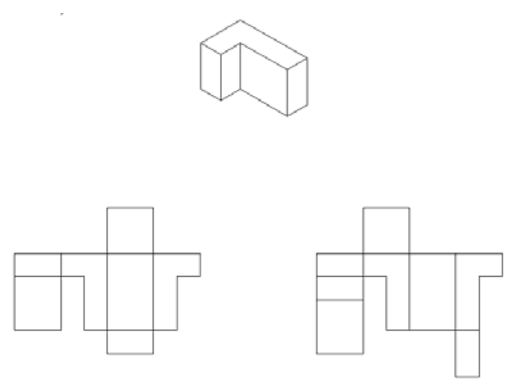
2D3D Recognition



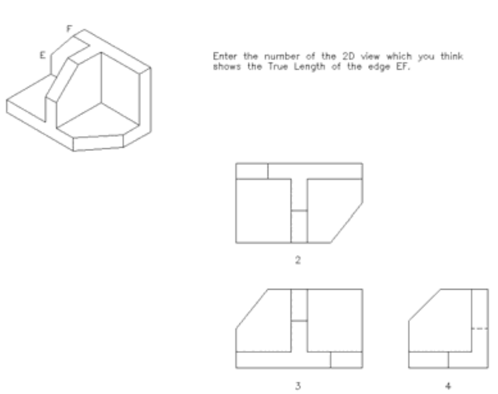


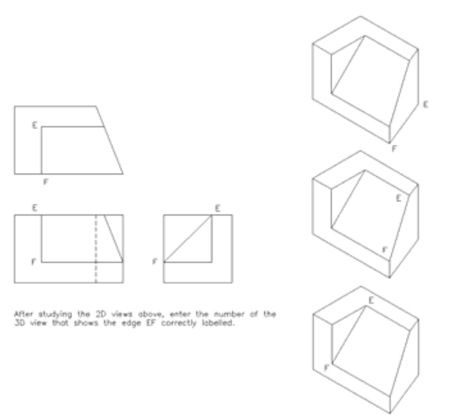
Correct Fold



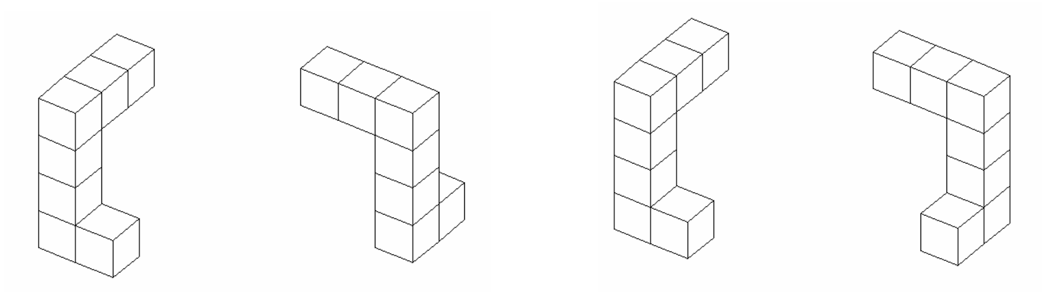


True Length Recognition

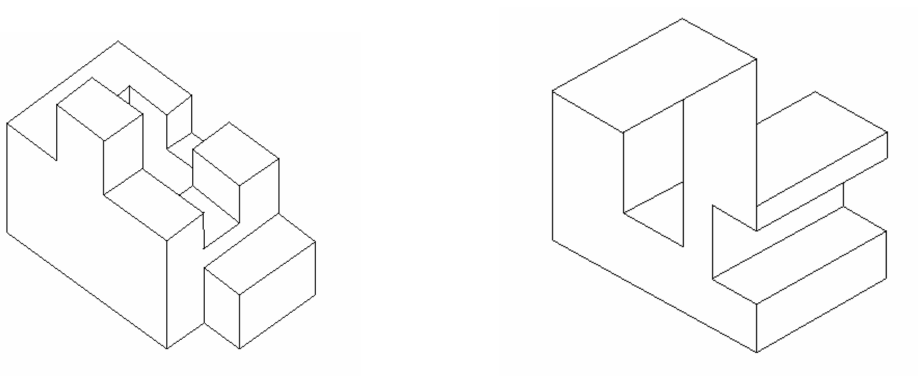




Mental Rotation



Object Decision



Dot Coordinate