Implications of Spatial Abilities on Design Thinking

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Abstract

The relationships between various cognitive characteristics and design creativity provide the necessity for consideration for design education. It can be argued that constructive perception ability that combines perception and conception and basic ability in visual reasoning composed of visual analysis, synthesis and representation in iterative nature are equally related with creative design ability. This paper reports findings of the application of a Spatial Ability measurement tool to first year design students and considers the results across three parameters, gender, University entrance Score and students' achievement in a first year Graphics course.

Keywords

Cognition, cross/trans/inter,multi, disciplinarity, Architecture, Learning

This paper reports on the application of a Spatial Ability test to first year design students in the School of Architecture and Built Environment at the University of Newcastle. The evaluation of the results gained from the 170 students provided some interesting considerations where the students' performance relative to their University Entrance Score, their performance in a Graphics based course and the performance based on gender. Firstly the paper will consider the role of spatial ability in the design activity as document in current literature.

The Relationship of Spatial Ability and Design

Design is a natural human activity present in many professions (such as engineering, industrial design and architecture). The design activity when utilised by the design professions provides a significant force for innovation and change in our societies. Despite the fact that the activity of design and the activity of science are tightly linked, design can be contrasted to science in that it is considered to be about imagining and synthesising new realities, rather than analysing and describing existing ones. Design can also be contrasted to art as it is essentially guided by human purposes and is directed towards the fulfillment of intended functions (Alexioua, et al. 2009). The distinctive nature of the design activity as illustrated by this emphasis on novelty and usefulness makes design fundamental to modern society.

Although design is customarily taken to be a high level cognitive ability, and many empirical and computational studies are focused on design cognition (Alexioua, Zamenopoulosa et al. 2009), there is to date very little research that touches on the biological or neurological basis of design (e.g. Cross, 1984, 1990; Goel and Grafman, 2000; Vartanian and Goel, 2005). On the other hand, there are many neurological studies that focus on creativity and aesthetics in art (e.g. Zeki, 1999; Martindale et al., 2007).Lloyd *et al.* (2007) argues that a major problem with a lot of research in this field is the poorly defined relationship between theory and empirical evidence. There is a sense of disconnect between the world of what design researchers talk about and the world of design activity itself. In addition, studies often come from a wide range of analytical approaches, including psychology, sociology, anthropology, grounded theory, and management studies. This diversity enriches the empirical-based study of designing but at the same time points to the absence of an agreed research methodology for design studies.

Definitions of design usually refer to the importance of "constructive forethought", or as Gregory (1987) states: "Design generally implies the action of intentional intelligence." A few common themes have emerged around the ways in which designers work and what designers do. Designers are said to (1) produce novel and unexpected solutions; (2) tolerate uncertainty and work with incomplete information; (3) apply imagination and constructive forethought to practical problems; and, (4) use drawings and other modeling media as a means of problem solving.

These themes provide us with an understanding of what designers do, however they do not inform us about the *Design Thinking* which underpins such design practice. Cross (1995, 2006) suggests that design aptitude consist of several key components including the ability to resolve ill-defined problems, adopt solution-focused strategies, employ abductive, productive and appositionial thinking, and use nonverbal, graphic/spatial modeling media.

This definition of design cognition acknowledges the particular ways that designers think, work and know. It separates designers' behavioral and cognitive processes from scientific and artistic forms of knowledge, both of which have tended to engulf design within their own epistemological and pedagogical frameworks. The unique nature of design processes suggest that there is a need to establish a distinct language and research of design, though care needs to be taken so that design is not reduced to static cognitive and behavioral categories for the sake of it (Allison 2008; see also Snodgrass and Coyne 1992).

Considering the crucial components of the design process, Kim and Maher (2008) defined the process of designing as a cognitive activity that involves the production of sequential representations of an artifact, both mental and external. Although further research is required on this matter, it can be argued that viewing design as a form of intelligence is productive; it focuses attention on design as a cognitive activity, it helps to identify and clarify features of design ability, and it offers a framework for developing further knowledge of the case for 'designerly' ways of knowing, thinking and acting.

Defining spatial ability

One of the more important cognitive components for designers is spatial ability. The concept of spatial ability refers to a complex process that designers utilize extensively in their design activity. Spatial ability has been defined as:

- the performance on tasks that require mental rotation of objects, the ability to understand how objects appear at different angles, and the ability to understand how objects relate to each other in space (Sutton & Williams 2007);
- "… the ability to mentally manipulate, rotate, twist, or invert pictorially presented stimulus objects" (McGee, 1979, p. 893);
- "… visual skills, spatial manipulation, recognizing the similarity of visual images, and imagining how visuals might appear in other orientations'' (Jonassen & Grabowski, 1993, p. 64);
- "… the ability to generate, retain, and manipulate abstract visual images (Lohman, 1979, p 188)";
- the ability to conceptualise links between reality and abstract; and
- the aptitude needed to mentally process three-dimensional images of objects (Fleisig *et al.* 2004).

Considered in their most basic form, spatial abilities form part of the visual thinking used in everyday life. Common activities, such as maneuvering a car along an unfamiliar road or rearranging furniture, require visual thinking. Spatial ability requirements escalate when higher order skills are needed as, for example, in the interpretation of technical drawings such as in building plans and in the process of translating these plans into buildings (McKim, 1980; Lajoie 2003). High spatial ability is therefore a requirement for design related activities where it is related to successful performance in real-world occupations such as architecture and engineering (Cronbach, 1970; Smith, 1964).

Spatial Ability and Design Learning

Spatial ability in the domain of design is essential for both learning and problem-solving, even when a problem is not specifically spatial (Alias et al. 2002; Roberts et al. 1997). From this it can be easily deduced that spatial ability plays an important role in design education and for the learning experiences of design students. There is a body of research (Sutton & Williams 2007; Sorby 2005; Potter & van de Merwe 2001) that indicates the importance of spatial ability in graphics-based courses and the implication of poor skills on success rates and career choices. However, despite there being a vast amount of research on spatial ability, there is very little known about the effects of spatial ability on design thinking and how it is developed through appropriate education programs. Furthermore, previous research on spatial ability tends to focus on one or two test types and neglects test types that specifically target spatial cognition relevant to disciplines such as design (Allahyar & Hunt, 2003).

Spatial ability has in the past been considered an innate ability. Recent research conducted at the University of Newcastle (Sutton & Williams, 2007) has, however, started to increase our understanding of spatial ability as well as of the effect it can have on students' performance in design related courses. A substantial part of spatial ability is 3D understanding; that is, the ability to extract information about 3D properties from two-dimensional (2D) representations (Sutton, Heathcote, & Bore, 2005). For the purpose of interpreting 2D drawings that are based on a notational system, design students require the ability to think and reason in 3D. By adopting the 3D Ability Test (3DAT), the projects reported here aimed to measure the spatial ability of students.

The studies on which this paper reports were conducted under laboratory conditions and in accordance with established psychological methodology protocols. Data were analysed using standard and appropriate statistical procedures. The underlying hypothesis was that no one spatial task is ideal when measuring the spatial performance of designers but that multiple subtests are required in order to gain a measure spatial performance. The studies used a range of paper ability tests that measures accuracy on a set of test items within a set time frame, and they 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. This paper only reports the results of the 3DAT. In what follows, we present the approach used to investigate students' spatial ability and report on the results of statistical procedures.

Testing Spatial Ability

3DAT is a computer-based instrument that measures choice accuracy and response time. In its present form, the 3DAT consists of 12 subtests. Each subtest aims to measure separate factors of spatial ability, often referred to as elements or spatial skills. There is disagreement in the literature about the number of spatial skills that make up spatial ability.

The 3DAT is delivered on a computer using psychological experimental research software (SuperLab Pro). It consists of 72 items that are divided into the 12 subtests mentioned above. The items are all made up of straight lines and flat planes, but they vary in form and are novel in design. They were created using a CAD package (AutoCAD) and saved in bitmap format to suit the experimental software. Below is a description of the broad areas that make up the subtests:

- 2D3D Recognition: Objects are presented as orthographic and isometric projections. Participants select which type of two alternatives 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 select which type of two alternatives match 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 cannot 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.
- The tests cover a comprehensive range of different components of spatial ability and provide a detailed understanding of the spatial ability of the participants. A range of the examples of these can be seen in Appendix 1.

Results

The study, of design students spatial ability attributes has yielded a range of interesting and, in some cases significant, results. There are three areas aspects of the results that stand out, namely:

- the disparity between gender when considering spatial abilities;
- the relationship between high university entry scores and spatial ability; and
- the relationship between spatial ability and success in university design courses.

Gender

The test results show a significant difference in the performance of male and female students in relation to different aspects of spatial ability. As illustrated in Figure 1, which shows the level of performance by gender, female students did not perform to the same level as their male peers.

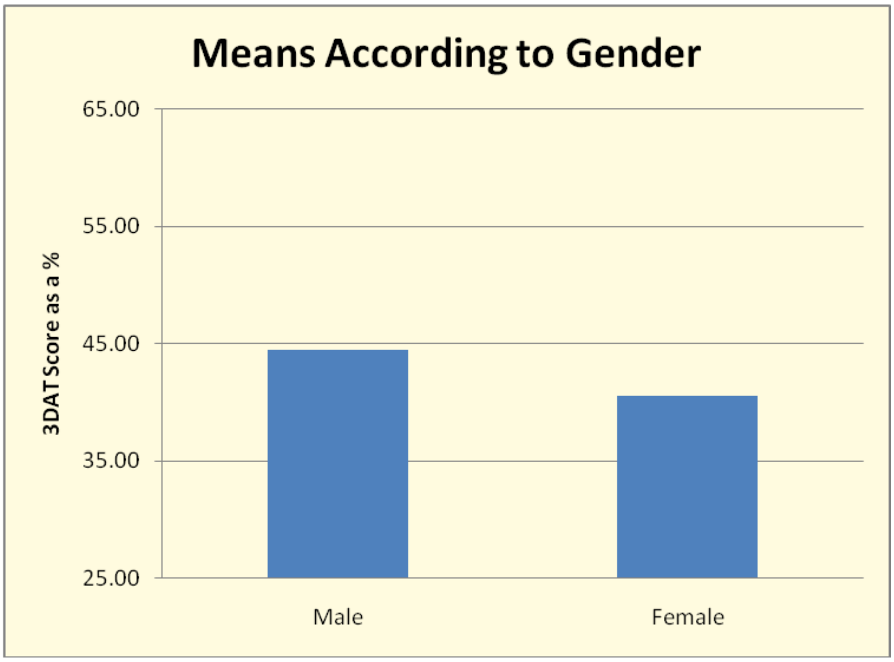

Figure 1 : Outcomes for Gender

The 12 subtests combined attained an overall mean score of 42.5%, with the males having a mean of 44.5% and females a mean of 40.5%. The female design students did not perform as well as their male counterparts on any of the singular subtests. Figure 2 illustrates the significant difference between male and female students on the 12 different subtests. This breakdown of the results makes the impact of gender even more apparent.

The performance of females across these fields is significantly lower than the males showing that females would find concepts that require such cognitive processes would not be able to function at the same level.

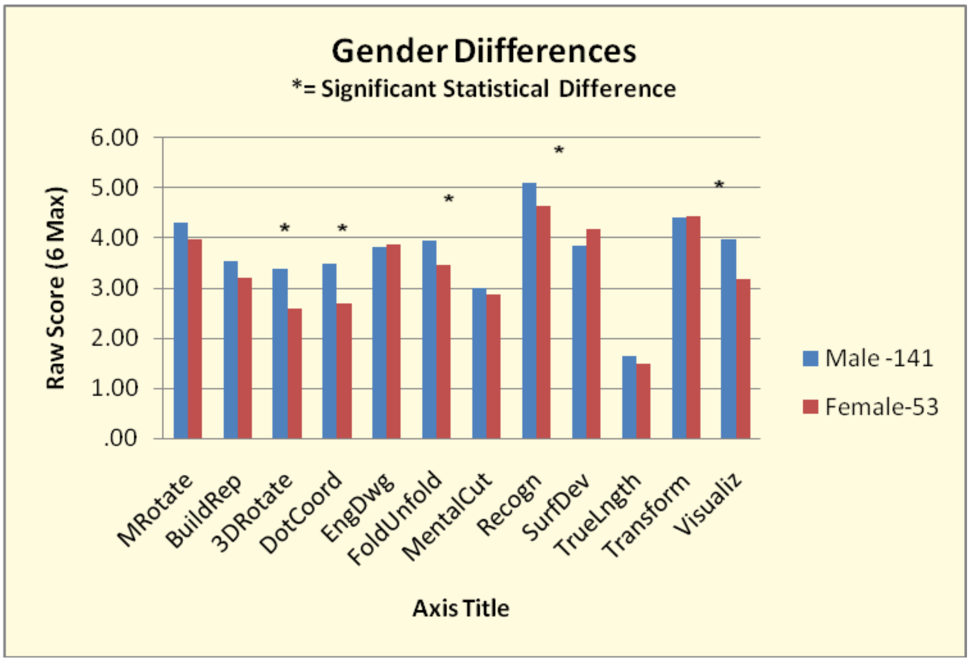

Figure 2: Performance of genders across the range of subtests

More research on this matter is required, and studies that will include other design discipline and other institutions are in planning. The results indicate that females experience more difficulty than their male peers when dealing with spatial problems and female students are likely to face greater difficulties with subjects that involve spatial ability aspects. The significant difference between male and female students across all the 12 tests raises a range of issues. It highlights the importance of preparing females for work in areas that require spatial abilities and consideration for educators as to how this divergence can best be addressed. The desire for increased female participation in the range of design disciplines at universities and in the work force accentuates the need to address this issue.

The preparation of students for university courses that require and utilise spatial ability needs to be a consideration of the secondary and perhaps even the primary school sector. Indications are that if exposed to appropriate experiences already at an early age, females are able to improve their abilities in this area.

Universities need to consider the abilities of female students when they enter design based courses or courses which would require application of spatial abilities. Curricula need to include experiences for females to that they are able to participate fully in subjects involving design or drawing and problem solving that requires spatial abilities.

The Relationship of Spatial Ability to UAI

One of the long held beliefs of universities is that high entry scores will ensure the quality of the students. Accordingly, it may be anticipated that there is a correlation between the novice designers' scores in spatial ability and their university entrance score. This assumption has a historical link with the inclusion of spatial ability type problems in traditional IQ tests. It is, however, evident from the results presented in Figure 3 that there is negligible correlation between university entry scores and spatial ability.

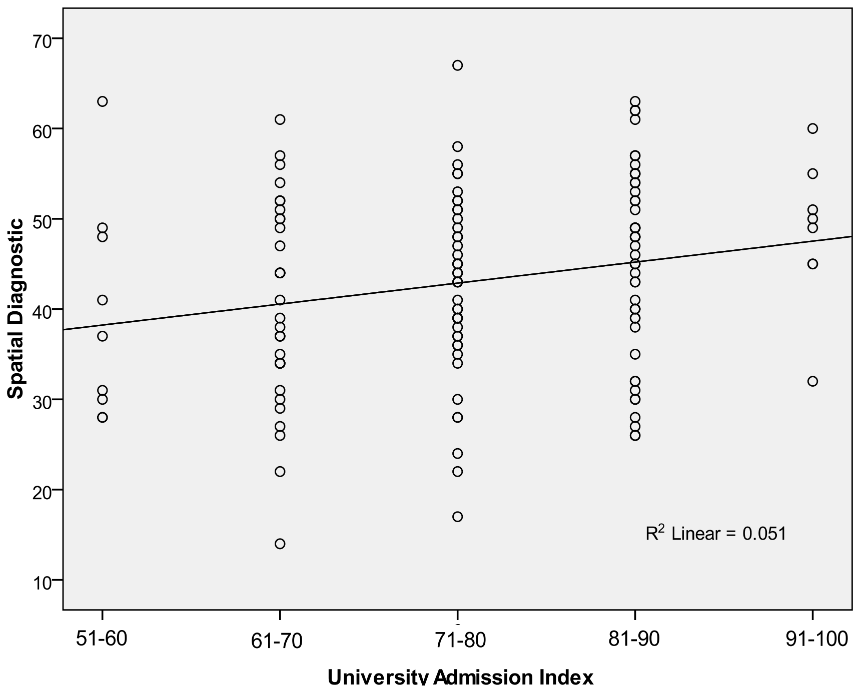

Figure 3: The relationship of the Course Score to the Student UAI

What is evidenced is that the students with higher UAI scores did score higher in the 3DAT when it is looked upon as a mean or average. But what this does not indicate is the range of the results in each grouping. This is evident where the spread of the results show that there is just as significant range of results in each university entry score deciles.

The relationship of UAI to performance in spatial ability provided some interesting outcomes. The project team expected a high positive relationship between the UAI performance and the spatial ability results. This was not confirmed by the results, which instead showed a low to medium positive relationship between these variables. This result suggests the need to consider the potential problems that students who enter university with a high UAI might have in subjects utilizing spatial abilities. Drawing and CAD courses are often part of the early curriculum structure of design programmes, requiring pre-existing spatial ability skills. Such skills are, however, not necessarily reflected in the UAI of the students. Obviously further study is required in this domain but, with such consistent results, the question must be asked about preparedness for study in some types of subjects. One factor that may impact on this situation is the experience level of the students undertaking the tests.

The material reported here suggests that students with high UAI do not perform as well as could be expected across the range of spatial ability tests. This implies that, firstly these students may not relate well to subjects that utilise spatial ability, and, secondly, that it is not possible to consider UAI as an indicator of expected performance when dealing with spatial ability problems.

The Relationship between Spatial Ability and Results in a University Course

This study investigated the relationship between course marks attained in a university undergraduate first year graphical communication course and the 3DAT to determine if the 3DAT could be used as a reasonable predictor of success in certain graphics based courses. Deno (1995) points to a deficiency in visualization skills as a reason for many design students withdrawing from graphics courses very early in their careers and considers addressing shortcomings would improve retention rates. In one detailed study (Blasko, Holliday-Darr, Mace, & Blasko-Drabik, 2004), a number of variables such as academic background, motivation, parental persuasion, verbal skills and spatial ability were tested to determine what might impact on student retention rates the most. The researchers found that scores on basic tests of spatial ability (e.g., mental rotation) were the best predictors of retention.

	BuildRep	DotCoord	EngDwg	FoldUnfold	Recogn	SurfDev	Visualiz	3DAT
Course Mark	.18*	.17*	.34**	.21**	.24**	.29**	.23**	.3**

*p is significant at the .05 level. **p is significant at the .01 level. Sample (n = 179).

Table 1: Correlation Between Arbe1100 Marks and the 3DAT and Subtests Scores

Correlation coefficients (r) for the Graphics course marks and the 3DAT and selected subtests are shown in Table 1. Correlations were statistically significant for 7 out of the 12 subtests and these are the subtests listed in Table 1. For effect size, r = .10 is considered to be low, r = .30 is considered to be medium and r = .50 is considered to be high (Cohen, 1992). Effect size is also termed practical significance and it is a measure of the extent of a relationship between two variables (e.g., Arbe versus 3DAT). Using this scale, the relationship between course marks and the 3DAT and each of its subtests shown in Table XX is in the low to medium range. Although the correlations are significant, the correlations are not strong. Using the 3DAT in its existing format at the time provides a modest predictor of success in a graphical communication course such as Arbe1100. However, the 3DAT has undergone a number of reviews and modifications in accordance with psychometric standards for test development since the testing with the participants reported in this study. These standards include item analysis, validity assessment and measures of internal consistency (reliability) of the test items in each subtest. We have confidence that the 3DAT is a more effective instrument in its current form and further testing is planned in 2010.

Conclusion

The 3DAT test for Spatial ability has now been evaluated and refined over a four year period and the statistical results gained from its use across a range of disciplines and levels in both Design disciplines and non-design disciplines has proved fruitful data but also a validation of the test. The result of the First Year Design Students doing a course in the School of Architecture and Built Environment School showed a range of interesting results across the three areas reported in this paper. Results indicate a statistically significant difference between male and female spatial performance, favouring males, and overall spatial performance showed only a marginal correlation with university entrance scores but the range of scores at any level was very broad with students at the top end of the UAI scoring very low results in the 3DAT test, inferring that the higher UAI students may not have high Spatial Skills and visa versa. Spatial performances were also compared with course results and indicate that spatial ability can be used as a moderate predictor of success in graphics based courses.

Further refinement will be undertaken of the test but more importantly the project now moves into a phase of resource development to develop online resource packages aimed at enhancing students' spatial ability and using the 3DAT as a self diagnostic stool.

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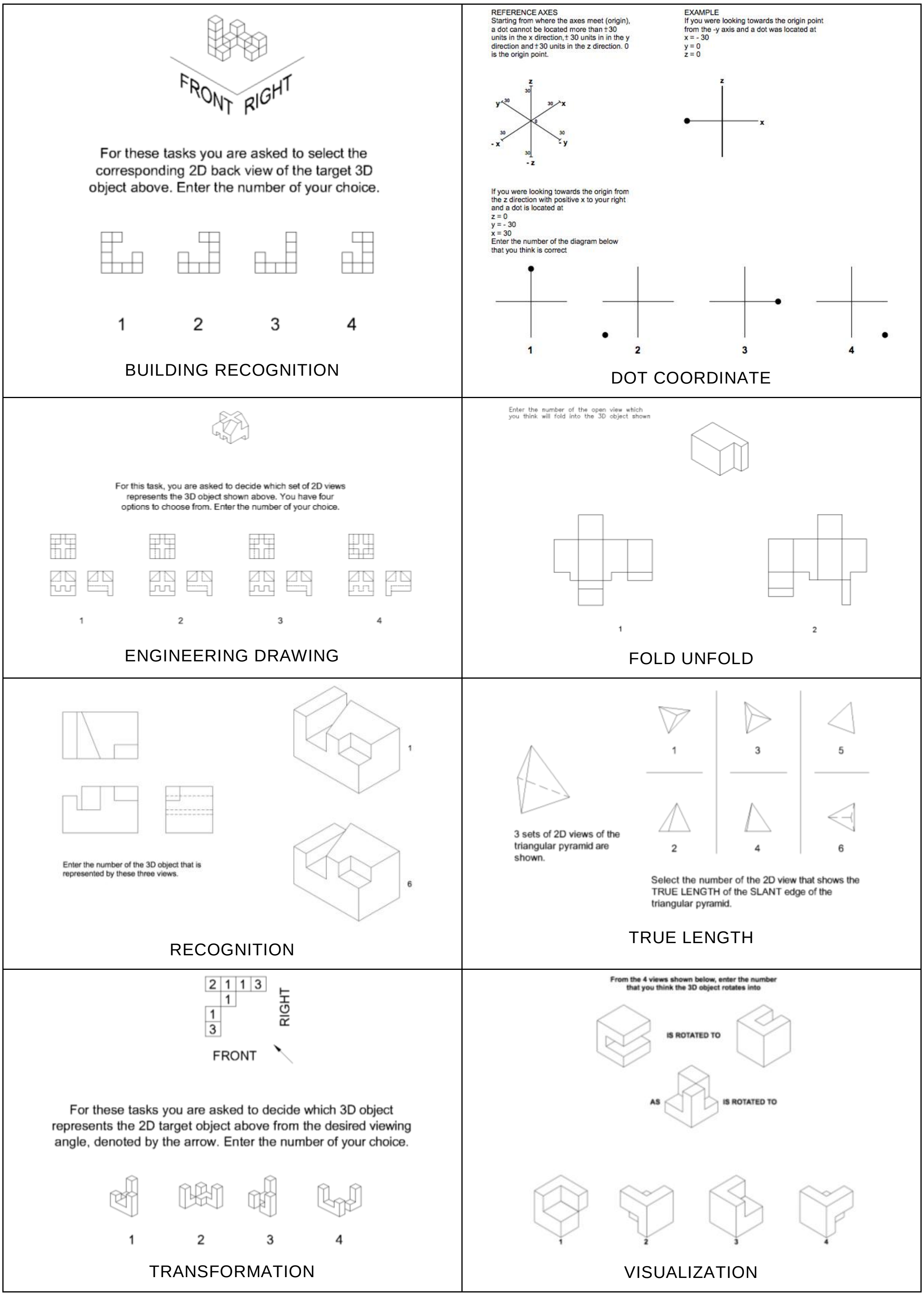
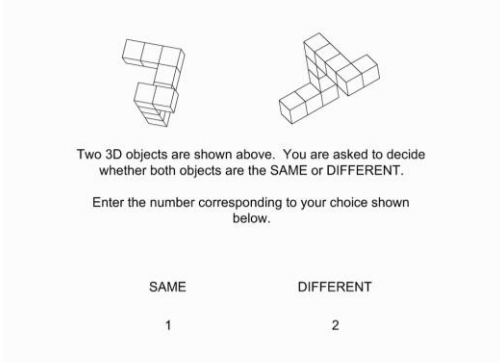
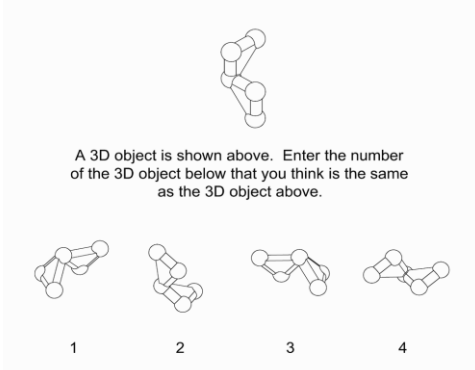
Appendix 1: Examples of Test Items

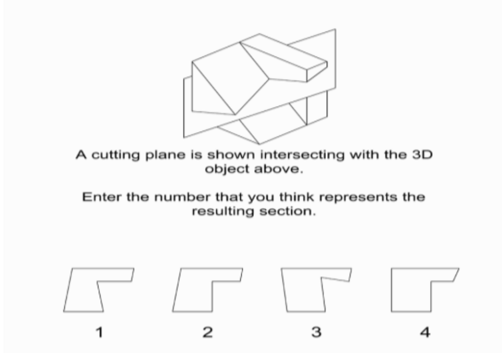




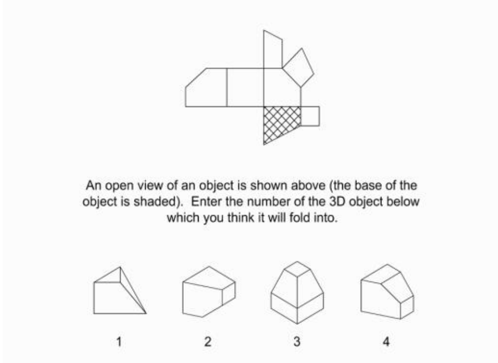
MENTAL ROTATION



3D MENTAL ROTATION



MENTAL CUTTING



SURFACE DEVELOPMENT

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