The relationship between spatial visualisation ability and problem solving in structural design

Maizam Alias†, Thomas R. Black‡ & David E. Gray‡

Kolej Universiti Teknologi Tun Hussein Onn, Johor, Malaysia†
University of Surrey, Guildford, England, United Kingdom‡

ABSTRACT: The aim of this study was to test whether spatial visualisation activities would affect problem-solving skills in structural design. A quasi-experimental design method of post-test only with a control group was employed to determine the effect of the prescribed intervention. The experimental group was taught spatial skills prior to the learning of the subject, while the control group had their normal lectures. There were 77 and 61 civil engineering students in the experimental and control group respectively. The two groups were equivalent with respect to age, gender proportion and academic ability. Two instruments, the Spatial Visualisation Ability Test Instrument (SVATI) and the Structural Design Instrument (SDI) had been specifically designed for the study. The reliability estimates for the SVATI and the SDI are 0.70 and 0.73 respectively. It was found that the experimental group had a statistically significantly higher score on the structural design measure compared to the control group and that the effect was especially significant on the understanding of structural behaviour. It was concluded that spatial visualisation ability aids in the understanding of structural behaviour and thus enhances problem solving in structural design.

INTRODUCTION

The inadequate level of design skills among graduate engineers has been of concern for some time. Factors attributed to the cause of the condition include the teaching approach in engineering education, where subjects are taught in isolation without much effort to integrate the acquired knowledge and understandings, the high emphasis on the analytical and the mathematical techniques at the expense of the qualitative reasoning techniques and the unstructured nature of design problems [1-6]. Efforts to improve design education have included making changes at the course structure level, as well as at the classroom level [4][7].

The present study involved intervention at the classroom level with one main aim: to determine the relationship between spatial visualisation ability and performance in structural design problem solving among civil engineering students. Spatial visualisation ability here is defined as *the ability to mentally manipulate, rotate, twist, or invert pictorially presented stimulus objects* [8].

Some support for the hypothesis, which links performance in structural design problem solving to Spatial Visualisation Ability (SVA), can be found in the literature. For example, Lienhard declares that spatial visualisation is one of the three key elements that characterise engineering design, the other two being *trial and error* and *cooperation* [9].

Further supporting literature are from SVA studies involving design related subjects, which have consistently shown the relevance of SVA to academic success in those subjects such as mathematics and technical subjects [10-12]. Another form of support for the hypothesis came from the results of learning task analyses on design tasks, which revealed a hierarchical relationship between SVA and structural design [13].

Lastly, the spatial nature of structural design problems and required structural design skills intuitively support an association between SVA and structural design problem solving. In fact, the definition for the understanding of structural behaviour, as affirmed by Fraser and Brohn, ie the ability to predict responses of structure to loads or applied deformations, closely resembles the definition of SVA [14-15].

SPATIAL VISUALISATION ABILITY STUDY

Overall, there is some support for the hypothesis that relates SVA to structural design problem solving. However, up until this stage, the argument for the relationship had only been a hypothetical one. Therefore, the aim of this study was to determine the relationship between SVA and problem solving in structural design through an empirical enquiry. The three specific research questions were as follows:

1. Is there a relationship between SVA and structural design problem solving among civil engineering students?
2. Does SVA ability affect performance in structural design problem solving among civil engineering students?
3. Does SVA equally affect learning outcomes at different cognitive emphasis?

This study is part of a larger study that investigated the relationship between attitudes towards sketching and drawing, instructions on spatial skills, spatial visualisation ability and problem solving in civil engineering.

A correlation design was used to determine the extent of the association between SVA and structural design problem solving, while a quasi-experimental design of post-test with a control group was adopted for the second and third research questions.

The population to which the findings could be generalised is the group of students who were undergoing the polytechnic civil engineering diploma programme. The diploma qualification is equivalent to the first year of a civil engineering degree programme. The sample for the correlation study involved two intact classes of final semester civil engineering diploma students enrolled at Ungku Omar Polytechnic, Ipoh, Malaysia, with n = 43. Participants in the study were administered the test on design problem solving at the end of the semester together with the test on SVA.

The samples for the cause and effect study involved two groups of civil engineering students from two consecutive semesters of a diploma programme. The control and the experimental group consisted of n = 61 and n = 77 students respectively. The two groups were equivalent with respect to age, gender proportion and academic ability. The control group followed the normal structural design class and had their structural design test at the end of the semester. The experimental group were prescribed spatial activities during the first week of the semester, followed by their normal structural design class, and were administered the structural design test at the end of the semester.

Instruments

Two instruments, the Spatial Visualisation Ability Test Instrument (SVATI) and the Structural Design Instrument (SDI) had been specifically designed for the study. The SVATI is made up of 28 items based on three types of spatial tasks, ie engineering drawing task, mental rotation task and cube construction task. These spatial tasks are considered to be valid measures of spatial visualisation ability as they have been successfully used in previous spatial ability studies [16-17]. The SVATI has a concurrent validity of 0.74 between itself and the Mental Rotation Test, a frequently used SVA measure [18]. The SVATI has an estimated Kuder Richardson reliability (KR20) of 0.70 and should be considered as reliable for the purpose of the study.

The SDI is made up of 24 mixed type of items. Collectively, the items measure problem solving ability in structural design. However, individually, the items are classified into three categories of items using the Bloom's Taxonomy of Learning Objectives [19]. The categories were based on the level of the desired learning outcomes that the items were designed to measure, ie knowledge level, application level and analysis and evaluation level.

For the knowledge items, students were tested on their knowledge of axis and planes in the context of column and beam bending. For the application items, the skills measured were the understanding of structural behaviour. Students demonstrated their understanding of structural behaviour qualitatively through sketches of deflected shapes of structures, bending moment and shear force distribution and directions of reactions as recommended by Brohn [15]. Finally, for the analysis and evaluation items, students analysed and evaluated given design proposals.

The SDI content includes analysis and design of simple reinforced concrete columns, beams and slabs, which is part of the design curriculum. To ensure sufficient content coverage, a table of specifications for the SDI was constructed and further validation of its content was obtained through consultations with three subject matter experts. Most of the items demand

qualitative analysis skills. The SDI has an estimated Cronbach alpha reliability coefficient of 0.73 and is deemed to be sufficiently reliable for the purpose of this study.

Spatial Activities

The prescribed spatial activities include generic, as well as specific, spatial activities that have been found to enhance spatial visualisation ability in the previous study [20]. The generic and specific spatial skill components have been identified through a task analysis on a chosen design task [13].

Generic spatial activities include sketching and drawing from observation, drawing from memory and model building activities. Activities were designed to provide learners with learning experiences that progress from the concrete to the more abstract ones. Concrete learning experiences are especially important for those learners who may not yet reach the formal operational stage of thinking.

According to previous studies, a substantial proportion of college students have yet to mature to the operational stage. In one study, 57-65% of college students are estimated to be at the operational stage, while in another study, the estimate is much lower, ie only 25% [21-22]. Generic spatial activities have been adapted from previous work [12][23-25].

Specific spatial activities include sketching of structural deformations based on observation, sketching from memory and sketching from imagination. Students predicted beam responses to a given set of applied loads and support conditions and demonstrated their ability by sketching the deflected shapes of the beam, the moment distributions and reactions.

DATA ANALYSIS AND RESULTS

A scatter diagram was drawn and the Pearson correlation coefficient was subsequently estimated to indicate the type and the strength of the association between structural design and SVA. A positive and modest correlation, $r = +0.48$, was found between the scores on the SDI and the SVATI. This correlation is statistically significant at the 5% level of significance. The index of determination was estimated at 23% indicating that 23% of the variances are common to the SVATI and the SDI. Although correlation exists between the scores on the SDI and the SVATI, a cause and effect relationship cannot be assumed.

For the cause and effect analysis, the mean for each group was computed and a test for equality in means was carried out. Table 1 shows the descriptive statistics for the two groups. The mean of the experimental group is 3.35 points higher than that of the control group.

Table 1: Descriptive statistics on the SDI for the control and the experimental groups.

Data	Control	Experiment
$\bar{x}$	23.99	27.34
s	6.94	12.03
n	77	61

A significance test was performed on the means using independent two-tailed t-test for equal variance. The use of the

equal variance *t*-test was justified as there was normality of distribution, homogeneity of variance as indicated by the non-significant *F*-test and independence of measure, which was the consequence of the research design. The result shows that the difference between the experimental and the control group is statistically significant where the calculated *t* (2.05) is larger than the $t_{critical}$ (1.98) at 5% level of significance.

SVA and Learning Outcomes at Different Cognitive Emphasis

Table 2 displays the descriptive statistics for the performance on the individual component of the SDI. Compared to the control group, the experimental group scored less on the knowledge component, more on the application component and less on the analysis and evaluation component.

Table 2: Mean and standard deviation on the individual component of the SDI.

Cognitive Emphasis	Treatment		Control	
	$\bar{x}$	s	$\bar{x}$	s
Knowledge	5.54	1.59	5.83	1.29
Application	16.59	8.49	9.78	3.63
Analysis and evaluation	5.21	4.79	8.38	4.59

The two-tailed *t*-test for equal variance was again used to test for significance for the same reason as given previously. The difference in means on the concept items between the control and the experimental group was not statistically significant at the 5% level of significance. The higher mean of the experimental group on the application items was statistically significant at the 5% level of significance where *t* (6.35) is greater than $t_{critical}$ (1.98) for *df* = 136, with p < 0.05. Results on the analysis and evaluation component showed that the control group did better than the experimental group and the difference was statistically significant.

DISCUSSION

An association between SVA and structural design problem solving was found, which is consistent with expectations. The positive effect of SVA on performance in structural design problem solving was also supported by the data, which is also consistent with initial expectations. However, results on the effect of SVA on the performance at different cognitive emphasis were mixed: ranging from no effect to a totally unexpected effect.

No difference in the performance on the concept items between the control and the experimental group, suggesting that SVA does not affect knowledge of concepts, was not totally beyond expectations. This is because the prescribed spatial activities did not specifically emphasise the role of axis in column and beam bending. Therefore, although the subjects manipulated beam models that produced bending, which naturally involve rotation, the relationships between the various elements that are involved in producing the beam deformations may not be clearly demonstrated.

On the application items, the mean of the experimental group is almost twice that of the control group, which is a considerable difference in the amount of learning. Therefore, this outcome is academically significant because it reinforces the view that,

with the appropriate teaching and learning strategy, learning can occur.

The outcome is especially encouraging for the teaching and learning of structural design especially where the understanding of structural behaviour is concerned. The outcome is made more noteworthy by the fact that the interval between the prescribed intervention and the transfer test (SDI) was four months apart. A possible explanation for this is that the concrete model, together with the freehand sketching, may have facilitated meaningful learning of structural behaviour. In other words, the use of the beam model to illustrate deflections, together with sketching to illustrate beam deflections and structural actions, may have facilitated the linking of the physical and concrete phenomena (deflection) to the more abstract ones (bending moments, etc). Thus, it facilitated the conceptual understanding of structural behaviour.

The experimental group performed less satisfactory on the analysis and evaluation items. This outcome is highly unexpected in view of the inference that could be made from it. For example, it could be inferred that the ability to analyse and evaluate a design is negatively affected by SVA. Since the control group did poorly on the understanding of structural behaviour, which is a pre-requisite for solving the analysis and evaluation items, it is unjustified to suggest that SVA causes negative learning transfer.

One factor that could have contributed to the unexpected outcome is poor time management on the part of the experimental group, indicated by their responses that appeared to be provided in haste. The investigated subjects might have spent too much time on the application items – in which they had confidence – leaving them with insufficient time to answer the remaining items, ie the analysis and evaluation items.

CONCLUSION

This study set out to determine if there is any relationship between SVA and problem solving in structural design. The findings show that not only there is an association between SVA and problem solving structural design, but the relationship is also causal in nature where SVA is found to affect problem solving in structural design in a positive way. However, the degree of effects varies depending on the cognitive emphasis.

The finding suggests that SVA has the most influence on the understanding of structural behaviour as indicated by the higher performance on the application items. However, SVA do not appear to support the learning of conceptual knowledge that are related to bending moments, axes and planes of references, which could be due to the weakness in the prescribed learning materials. The effect of SVA on the analysis and evaluation learning outcome is inconclusive.

In conclusion, SVA has been found to affect problem solving in structural design in a positive way where, most significant academic-wise, is its impact on the understanding of structural behaviour, which is the key skill in ensuring successful design of structures. However, further studies are necessary in order to ascertain the academic impact of SVA on various learning outcomes with different cognitive emphasis.

REFERENCES

1. Eyre, J.R., Morreau, P., Croll, J. and Addis, W., Developing structural designers: a new graduate course at UCL. *The Structural Engineer*, 72, **4**, 232-234 (1994).
2. Nicolai, L.M., Viewpoint: an industry view of engineering design education. *Inter. J. of Engng. Educ.*, 14, **1**, 7-13 (1998).
3. Korn, J., Fundamental problems in engineering design course. *European J. of Engng. Educ.*, 19, **2**, 165-174 (1994).
4. Noble, J.S., An approach for engineering curriculum integration in capstone design courses. *J. of Engng. Educ.*, 14, **3**, 197-203 (1998).
5. Addis, W., *Structural Engineering: the Nature of Theory and Design.* Chichester: Ellis Horwood (1990).
6. Shaw, W.G., *Educational Requirements for Avoidance of Structural Inadequacy*. In: Institute of Structural Engineers (ISE), Structural Failures in Building. London: ISE, 65-70 (1984).
7. Kartam, N.A., Integrating design into engineering education. *Inter. J. of Engng. Educ.*, 14, **2**, 130-135 (1998).
8. McGee, M.G., Human spatial abilities: psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin*, 86, **5**, 889-918 (1979).
9. Lienhard, J.H., A future of design: a question of visualisation. *Proc. ASME Design Conf.*, Boston, USA (1995), http://www.uh.edu/engines/design.htm
10. Winkel, B.J., In plane view: an exercise in visualisation. *Inter. J. of Mathematics Educ. Science and Technology*, 28, **4**, 599-607 (1997).
11. Baartmans, B.G. and Sorby, S.A., Making connections: spatial skills and engineering drawings. *The Mathematics Teacher*, 89, **4**, 348-357 (1996).
12. Sorby, S.A., Spatial abilities and their relationships to Computer Aided Design instruction. *Proc. 1999 ASEE Annual Conf.*, Session 1438 (1999), http://www.asee.org/conferences/search/99conf577.PDF
13. Alias, M., Unpublished doctoral thesis. University of Surrey, Guildford, UK (2000).
14. Fraser, D.J., *Conceptual Design and Preliminary Analysis of Structures.* New York: Pitman Publishing (1981).
15. Brohn, D., *Understanding Structural Behaviour Analysis* (2nd edn). Oxford: BSP Professional Books (1991).
16. Embretson, S.E., Cognitive design principles and the successful performer: a study on spatial ability. *J. of Educ. Measurement*, 33, **1**, 29-39 (1996).
17. Shepard, R.N. and Cooper, L.A., *Epilogue to Part 1: Mental Rotation*. In: Shepard, R.N. and Cooper, L.A. (Eds), Mental Images and their Transformations. Cambridge: MIT Press (1982).
18. Vandenberg, S.G. and Kuse, A.R., Mental rotations: a group test of three dimensional spatial visualisation. *Perceptual and Motor Skills*, 47, 599-604 (1978).
19. Bloom, B.S., *Taxonomy of Educational Objectives: The Classification of Educational Goals, Cognitive Domain*. London: Longmans (1956).
20. Alias, M., Black, T.R. and Gray D.E., Effects of instructions on spatial visualisation ability in civil engineering students. *Inter. Educ. J.*, 3, **1**, 1-12 (2002), http://iej.cjb.net
21. Lawson, A.E. and Blake, A.J.D., Concrete and formal thinking abilities in high school biology students as measured by three separate instruments. *J. of Research in Science Teaching*, 13, **3**, 227-235 (1976).
22. Killian, C.R., Cognitive development of college freshmen. *J. of Research in Science Teaching*, 16, **4**, 347-350 (1979).
23. Izard, J., Developing spatial skills with three-dimensional puzzles. *Arithmatic Teacher*, 37, **6**, 44-47 (1990).
24. Baartmans, B.G. and Sorby, S.A., *Instructors' Resource Manual: Introduction to 3-D Spatial Visualisation.* Englewood Cliffs: Prentice Hall (1996b).
25. Lappan, G., Phillips, E.A. and Winter, M.J., Activities: spatial visualisation. *Mathematics Teacher*, 77, **8**, 618-625 (1984).