EFFECT OF INSTRUCTION ON SPATIAL VISUALISATION ABILITY IN CIVIL ENGINEERING STUDENTS

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Effect of Instructions on Spatial Visualisation Ability in Civil Engineering Students

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The aim of this study was to test whether manipulative and sketching activities could influence spatial visualisation ability in engineering students. A pre- and post-test quasi-experimental design was employed using two intact classes of civil engineering students from Malaysian polytechnics. The treatment group (n = 29) manipulated objects and learnt to sketch from observation and imagination during their structural design class, while the control group, (n = 28) had their regular structural design class. The treatment group achieved a statistically significant gain in spatial visualisation ability compared to the control group. A statistically significant difference was neither found between gender irrespective of types of instruction nor for the interaction effect. It was concluded that the spatial activities enhances students' spatial visualisation ability and both male and female engineering students benefited equally from the intervention.

Teaching and learning, spatial activities, structural design, spatial visualisation ability, civil engineering

INTRODUCTION

Spatial visualisation ability is a subset of spatial ability - one of the factors of human intelligence structure. Spatial visualisation ability has been defined as, " the ability to mentally manipulate, rotate, twist, or invert pictorially presented stimulus objects." (McGee, 1979, p. 893). This multi-faceted ability helps engineers including civil engineers to conceptualise links between reality and the abstract model of that reality. For example, in the analysis of a loaded beam structure, the deflected shape of the beam is the reality and the mathematical equation chosen (often unseen in a computer design package) to represent this deflected shape is the abstract model of that reality. A civil engineer needs first to have an intuitive understanding of the interactive relationships among structural components before he could begin to predict the deflected shape, which leads to the identification of the abstract model. This intuitive understanding is also essential to civil engineers in another way. It helps them in visualising, predicting, designing and checking for the worst possible combination of loads on a given structure. In the design of a reinforced concrete design for example, the ability to visualise aids the engineer in the prediction of critical loading conditions, which is necessary in reaching an adequate reinforcement design.

Spatial visualisation ability has also been found to be essential to a student's success in some engineering related subjects such as calculus (Winkle, 1997), mathematics, (Battista, Wheatley and Talsma, 1989), engineering drawing (Sorby and Baartmans, 1996a) and computer-aided design (Sorby, 1999). Early indication for a positive relationship between this ability and structural design has also been found. Alias (2000) carried out a learning task analysis on the design of a reinforced concrete column - an area that demands a wide variety of structural design skills - and discovered that spatial skills are pre-requisite to the learning of column design suggesting that spatial visualisation ability may be essential to the success of structural design.

Overall, spatial visualisation ability may be critical to learning and problem solving in civil engineering especially to the learning of subject matter that demands spatial strategies such as structural design, engineering mathematics and soil mechanics. There has also been some suggestions that spatial ability is relevant to problem solving that is not dependent on spatial strategies proposed by Roberts, Gilmore and Wood (1997). Roberts, et al. proposed that in cases where non-spatial strategies are required, spatial ability influences the degree to which a problem solver is able to develop and evaluate these strategies.

In summary, spatial visualisation ability appears to be necessary to problem solving in engineering related areas that requires spatial as well as non-spatial strategies. Therefore, a better understanding of this ability should be potentially beneficial to the engineering education and profession.

FACTORS CONTRIBUTING TO DIFFERENCES IN SPATIAL VISUALISATION ABILITY

Differences in spatial visualisation ability and its acquisition have been attributed to a number of variables, including cognitive development, spatial experiences, gender and aptitude.

Cognitive development

According to Piaget and Inhelder (1971), a person's cognitive development determines the potential of what he/she could achieve. Four stages of cognitive development have been suggested, that is, (i) the sensori-motor stage, (ii) the pre-operational stage, (iii) the concrete operational stage, and (iv) the formal operational stage. A person who is at the concrete operational stage " always starts with experience and makes limited interpolations and extrapolations from the data available to his senses" (Piaget in Phillips, 1969, p. 104). On the other hand, a person at the formal operational stage does not need to experience in order to generate and evaluate propositions. As such, a formal operational thinker can be expected to make use of a variety of spatial possibilities and to have better spatial skills compared to those who have yet to reach this stage. According to Piaget and Inhelder (1971), children start to develop their formal operational skills at the age of 13; reaching their maximum potential by the age of 17, suggesting that students in post secondary education are formal operational thinkers. However, later studies have shown a high percentage of post-secondary students who have yet to reach the formal operational stage (Killian, 1979; Reesink, 1985). This has significant implications for teaching even in higher education, since reaching the formal operational stage is a result of a combination of maturation and experience. While maturation may come with age, experience is most likely to be the consequence of education.

Experiences

Spatial experiences - acquired through life experiences or formal education - have been suggested to contribute to differences in spatial visualisation ability. Deno (1995) finds that spatial experiences in non-academic subjects are correlated to spatial visualisation ability in engineering students. He also finds indications of differential effects of spatial experiences on gender. For example, playing with construction block type of toys is found to be a good predictor of male ability while activities that are visual and less tactile are good predictors for females. This has implications for children growing up in non-technological societies who lack play experiences and toys common in more developed countries.

Ben-Chaim, Lappan and Houang (1988) find that spatial activities that require the subjects to construct, evaluate and sketch models of buildings created from cubes could enhance spatial visualisation ability. Lord (1985) also observes an increase in spatial visualisation ability in his subjects of college students after undergoing planes through solids type of interventions. So did Seddon, Eniaiyeju and Jusoh (1984) who find that his group of 19 to 30 year old subjects benefits from instructions on orthographic projections.

Since spatial visualisation ability is a multifaceted ability, any attempt to improve the ability may influence the acquisition of one aspect of it while not the others as demonstrated by Zavotka (1987). Zavotka finds that while her students improve on their orthographic projection skills after following a program on computer animated graphics, they however, do not improve on their mental rotation skills. She finds that the students' performance on the mental rotation measure is significantly affected by the sequence of the films that are shown to them, that is, wire-frame to solid or vice versa. Interestingly, Braukmann and Pedras (1993) find that different spatial activities do not necessarily bring about a difference in performance on spatial ability. They find that using traditional drafting equipment is as effective as a using computer aided design in enhancing spatial skills in engineering students.

It appears that providing diverse spatial activities may be the key to enhancing overall spatial visualisation ability as illustrated by Sorby and Baartmans (1996a). Sorby and Baartmans prescribed diverse spatial activities to their engineering students, ranging from manipulation of concrete models to computer visualisation activities, and find that they improve greatly in their spatial visualisation ability as measured by The Purdue Spatial Visualisation Test.

In conclusion, the findings from previous studies support the hypothesis that spatial visualisation ability is affected by spatial experiences and the effect could be on overall or some aspects of the ability depending on the types of experiences. The impact of different types of spatial activities on spatial ability was taken into account in the design of teaching and learning activities for this study.

Gender

Findings from past studies indicate possible relationship between spatial visualisation ability and gender. For example, Vandenberg and Kuse (1978) and Hamilton (1995) find that males' perform better than females' on spatial mental rotation tasks, an indicator of spatial visualisation ability. Ben-Chaim, et al., (1988) also find that prior to instruction, boys in middle school were better in their spatial visualisation ability compared to girls although these differences disappeared after instruction on spatial skills.

However, some research findings are showing evidence for superior performance by certain groups of females. For example, Eisenberg and McGinty (1977) find that groups of female university students who enrolled in two types of mathematics program (i) calculus, and (ii) business statistics, performed better on the spatial visualisation measure compared to their male counterparts. The performances of the groups enrolled in the (iii) remedial mathematics, and (iv) mathematics for elementary school teachers program were however reversed.

As there is no clear relationship between gender and spatial visualisation ability, gender was considered as a potential source of confounding in the study.

Aptitude

Studies have also indicated some form of relationship between aptitude (general intelligence) and spatial visualisation ability. Aptitude has been shown to affect choice of strategy (Kyllonen, Lohman and Snow, 1984) and choice of strategy has been shown to affect performance on spatial tests, as indicators of spatial ability (Schultz, 1991). In brief, aptitude is related to spatial visualisation ability. Therefore, aptitude was also treated as a source of confounding in the study that needed to be controlled.

METHODOLOGY

Research questions and statistical hypotheses

Three research questions were investigated.

1. Could spatial visualisation ability of civil engineering students be improved through spatial activities consisting primarily of object manipulations and free hand sketching?
2. Is there a difference in spatial visualisation ability between males and females engineering students?
3. Do these spatial activities affect males and female students differently?

The three null-hypotheses were:

a) there will be no statistically significant difference between the experimental and control group in their mean gain scores on the Spatial Visualisation Ability measure irrespective of gender;

b) there will be no statistically significant difference between males and females in their spatial visualisation ability mean gain scores as measured by the Spatial Visualisation Ability measure irrespective of treatments; and

c) there will be no statistically significant interactions between gender and treatments.

Research variables

The dependent variable was the gain score on the test instrument that is, the difference between the post-test score and the pre-test score. The independent variables were gender (male and female) and types of learning program (prescribed specific spatial activities and not prescribed).

Research design and procedure

A quasi-experimental design method, as intact classes, were used, with pre and post-tests, with one group as a control was adopted for the study. Pre-tests on spatial visualisation ability were administered to both groups following which, the experimental group carried out some spatial activities as part of their structural design class over a period of one week. At the same time, the control group followed their normal structural design class. At the end of the week, spatial visualisation ability post-tests were administered to both groups. The short interval between the pre- and post-test was an advantage as it removed maturation effects from being a source of confounding.

Research Population

The population for the study was the civil engineering diploma students in Malaysian polytechnics. Malaysian polytechnics are post-secondary institutions, which train technical personnel in the three major areas of engineering, civil, mechanical and electrical engineering. These polytechnics offer 2-year certificate and 3-year diploma programs to secondary school leavers (age 16+). Diploma recipients of polytechnic engineering programs may either seek employment as assistants to engineers or further their studies to become engineers themselves. For this reason, the polytechnic diploma program is designed to be the equivalent of the first-year degree program in Malaysian universities to enable the graduates not only to seek employment but also to further their studies in engineering.

Although no spatial ability studies have been carried out on polytechnic students prior to this study, they were expected to have some spatial visualisation skills, which they acquired through the drafting courses taken in their earlier semesters. The engineering drafting course however, was designed primarily to develop draughtsmanship skills (Malaysian Ministry of Education, 1991) in these engineering students.

In this study, we aimed to discover whether a few hours of spatial activities involving object manipulations and free hand sketching could further improve spatial visualisation ability of these civil engineering students.

Research Sample

The experimental group was a class of civil engineering diploma students from Ungku Omar polytechnic while the control was the corresponding class from Port Dickson polytechnic. The average age of the experimental and control groups were 21.7 years and 21.5 years respectively. The proportions of males and females in both groups were similar and consistent with the ratio for all civil engineering students.

As shown by previous studies (Killian, 1979) secondary school leavers could still be pre-operational thinkers. Therefore, it was logical to assume that the samples were a combination of formal operations and concrete operations (or transitional thinkers. Nevertheless, a proportion of the non-formal to formal operations thinkers was expected to be comparable in both groups. This was a consequence of the random placement procedure of students into polytechnics practised by the Ministry of Education. Consequently, non-comparable groups with respect to formal or non-formal operations thinkers were not anticipated to be a source of confounding.

Teaching and learning materials

The learning activities prescribed for the study were designed with Piaget's learning theory in mind, that is, a person learns progressively from the concrete to the abstract. Although the major application of Piaget's theory of learning and stage theory was to children, it is also equally applicable to adults (Sutherland, 1999).

The purpose of these activities was to develop generic spatial visualisation skills as well as structural engineering specific skills. Initially, subjects used building blocks as aids to visualisation. Subjects also sketched objects (constructed from blocks) from observation and imagination. The generic activities were adapted from Izard (1990), Baartmans and Sorby (1996), Sorby and Baartmaan (1996b) and Lappan, Phillips and Winter (1984). The structural engineering specific activities consisted of manipulations of beam models, which were developed after a consultation with a civil engineering lecturer (C. Howard, personal communication, April, 1998) and sketching of structural diagrams, which were derived from

Brohn (1990). The overall emphasis was on concrete activities, which have been shown to benefit both formal operational and pre-operational thinkers.

Instrumentation

The spatial visualisation ability instrument was specifically designed for the study. To give a comprehensive measure of spatial visualisation ability, the instrument employed three types of spatial tasks: cube construction tasks, engineering drawing and mental rotation tasks. For each test item, subjects were instructed to choose one from four alternatives. Examples of the items are illustrated in Figures 1, 2 and 3. The instrument consisted of 28 items, 10 on the first task (Section I), 11 on the second task (Section II) and seven on the third task (Section III). The instrument had a Kuder-Richardson 20 (KR20) coefficient of 0.70 and a concurrent validity of 0.74 with the Vandenberg Mental Rotation Test (Vandenberg, 1971). The KR20 coefficients for Sections I, II and III were 0.55, 0.43 and 0.53 respectively. The validity of these tasks as measures of spatial visualisation ability has been established in other studies.

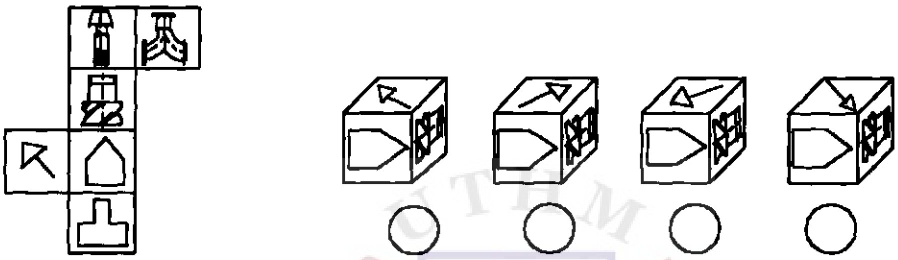

Figure 1. An example of a cube construction item

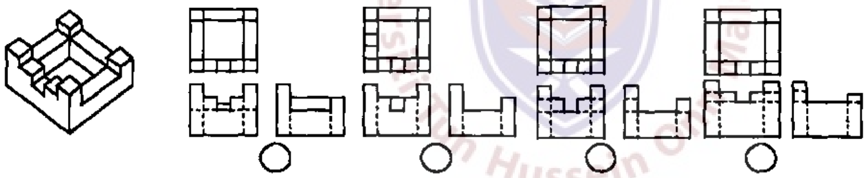

Figure 2. An example of an engineering drawing item of Type 1

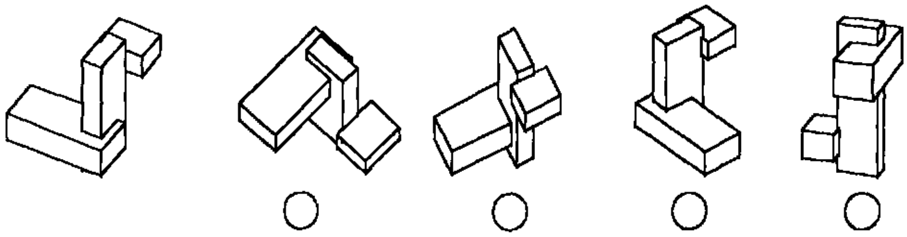

Figure 3. An example of a mental rotation item

RESULTS

Table 1 displays the means $\bar{x}$, standard deviations s on the overall test instrument and sample sizes n employed in the study. The unequal sample sizes were a consequence of using intact classes of students.

Table 1. Means $\bar{x}$, standard deviations *s*, on the spatial ability instrument and the corresponding sample sizes *n*

		Control	Experimental	Gender main effect
Female	$\bar{x}$ =	3.00	3.36	3.21
	s =	1.77	2.94	2.46
	n_f =	8	11	19
Male	$\bar{x}$ =	3.00	5.28	4.08
	s =	3.01	2.4	2.94
	n_m =	20	18	38
Treatment main effect	$\bar{x}$ =	3.00	4.55	3.79
	s =	2.68	2.73	2.8
	n =	28	29	57

The null hypotheses of no difference in means of the gain scores between groups and within groups were tested using an analysis of variance (ANOVA). A statistically significant difference was found between the means of the gain scores of the experimental and the control group (Table 2) indicating that the difference was unlikely to have occurred by chance alone although the statistical power was only 0.53. The assumption is that all extraneous variables were controlled for and therefore, the treatment was the likely cause of the difference. Statistical significance is not found for the results on the gender main effects or the interaction effect between gender and treatment.

A *post-hoc* analysis was not carried out on the result, as there was no statistically significant interaction.

Table 2: A two way ANOVA on the SVATI gain scores using worksheet in Excel from Black (1999)

	SS	*df*	*MS(s^2est)*	*F*	$F_{critical}$	α	*Outcome*
Gender	9.55	1	11.40	1.44	4.02	0.05	n.s
Treatment	34.30	1	29.96	5.16	4.02	0.05	$p<0.05$
Interaction	12.20	1	12.73	1.84	4.02	0.05	n.s
Within	352.34	53	6.65				
Total	408.43	56					

Results on the individual group of spatial task

As explained earlier, the spatial visualisation instrument employed three types of spatial tasks, each of which were postulated to require slightly different solving strategies or skills. Analysing the subjects' performance on the individual group of tasks may be advantageous as it may yield information on the types of spatial skills that benefit most from the prescribed spatial activities and information on the relationships between gender, type of skills and learning gains, if any.

Means and standard deviations on the cube construction items are displayed in Table 3. Clearly, the differences between the means for female and male groups irrespective of treatment are very small and unlikely to be statistically significant.

Table 3: Means $\bar{x}$, standard deviations *s*, on the cube construction items and sample sizes *n*

		Control	Experimental	Gender main effect
Female	$\bar{x}$ =	1.38	0.55	0.96
	s =	1.69	0.92	1.45
	n_f =	8	11	19
Male	$\bar{x}$ =	0.70	1.28	0.99
	s =	1.60	2.27	1.98
	n_m =	20	18	38
Treatment main effect	$\bar{x}$ =	0.89	1.00	0.97
	s =	1.65	1.99	1.81
	n =	28	29	57

The difference between the means of the gain scores for the control and the experimental groups irrespective of gender is also very small and unlikely to be statistically significant. There is however, some indication of dis-ordinal interaction effect between gender and treatment as indicated by the large variations among the means in the first four cells.

However, testing the null hypotheses of no difference in means of the gain scores for the interaction effect using ANOVA does not give a statistically significant result ($p > 0.05$). Statistical significance is also not found for the treatment main effect and for the gender main effect.

On the engineering drawing items (results displayed in Table 4), the difference in means of the gain scores across treatments irrespective of gender is relatively large giving an indication of a main treatment effect. The difference between gender means irrespective of treatments is also relatively large indicating a possibility for a statistically significant difference between means for genders.

Table 4: Means $\bar{x}$, standard deviations *s*, on the engineering drawing items and sample sizes *n*

		Control	Experimental	Gender main effect
Female	$\bar{x}$ =	0.50	2.00	1.25
	s =	1.41	2.49	2.19
	n_f =	8	11	19
Male	$\bar{x}$ =	1.50	2.83	2.17
	s =	2.35	2.01	2.27
	n_m =	20	18	38
Treatment main effect	$\bar{x}$ =	1.21	2.52	1.71
	s =	2.15	2.20	2.25
	n =	28	29	57

As expected, a statistically significant result was found for the treatment main effect as shown in Table 5 with a statistical power of 0.55. Surprisingly, statistical significance was not found for the gender main effect or the interaction effect.

Finally, no statistical significance was found on the mental rotation items for all the hypotheses tested.

Table 5: A two way ANOVA on the gain scores for the engineering drawing items using worksheet in Excel from Black (1999)

	SS	*df*	*MS(s^2est)*	*F*	$F_{critical}$	α	*Outcome*
Gender	10.46	1	10.46	2.36	4.02	0.05	n.s
Treatment	21.12	1.00	21.12	4.76	4.02	0.05	$p<0.05$
Interaction	1.48	1	1.48	0.33	4.02	0.05	n.s
Within	235.26	53	4.44				
Total	268.32	56					

DISCUSSION

The positive effects of teaching and learning on spatial visualisation ability found in this study are consistent with those from previous studies where similar teaching interactions had been used (Lord, 1985; Ben-Chaim, et al., 1988; Tillotson, 1984; Seddon, et al., 1984; Sorby and Baartmans, 1996a).

The absence of gender related differences in this study is however, in contradiction with previous research findings, which show poorer performance of females compared to males on spatial visualisation ability tasks (Ben-Chaim, et al., 1988; Eisenberg and McGinty, 1977; Allen and Hogeland, 1978). One possible explanation is that the types of spatial tasks employed in the present study were not the ones that tend to elicit gender differences. Most reported findings on gender differences are on the mental rotation tasks (Hamilton, 1995; Vandenberg, 1978) while findings on other types of spatial tasks are inconsistent. Alyman and Peters (1993) for example, find that out of nine spatial tasks – tasks involving everyday objects and settings - males only perform better on two, one of which is a mental rotation task and the effect size was less than 0.100. Therefore, even if females are weak in executing mental rotation of whole objects, they may be good in executing other spatial visualisation processes. The spatial visualisation ability instrument, which consisted of three types of spatial tasks, may have provided the female subjects with the opportunity to demonstrate the full spectrum of their spatial visualisation skills and thus performed equally well as the male subjects.

Another possible explanation is similarity in the types of spatial experiences of females and males in the study. Since females in this study were students who chose to study civil engineering – a male dominated field – it is likely for them to have some shared characteristics, such as shared spatial experiences. For example, similar spatial experiences early in life between males and females in this study, which leads to equivalent level of spatial ability, may have dictated their courses preference, which might explain the absence of gender-related differences in spatial visualisation ability of the samples. Furthermore, the females in the present study had had similar skills training (reading and interpreting engineering drawings as their male counterparts, in contrast to the females in the previously cited studies. This training might have wiped out or reduced considerably the initial difference in spatial skills if it existed. In brief, most probably there is no difference in spatial visualisation ability between males and females engineering students in the study.

On the individual components of the ability instrument, statistical significance was only found for the treatment main effect on the engineering drawing items. This is not surprising, as the subjects were familiar with engineering drawing. Therefore, the prescribed spatial activities may have facilitated the development of the most appropriate spatial strategies leading to better performance on the given tasks.

Lack of treatment effect on the cube construction items was, however, contrary to expectations. Nevertheless, the reliability of this particular instrument is only 0.55, so the finding must be treated with caution.

Similarly, lack of statistical significance in any of the hypotheses tested for the mental rotation items was also unexpected. Several factors could have contributed to this outcome. First, there was lack of shared characteristics between the teaching and learning materials and the test items. The learning materials consisted of relatively simple objects (constructed from building cubes) with square and non-slanting surfaces, while the test items were representations of complex objects, some with slanting and non-rectangular surfaces. Reported gains in mental rotation skills are mostly acquired through transfer tasks that were very similar to the practice tasks (Seddon and Shubber, 1985; Shubbar, 1990).

Secondly, implicit teaching of mental rotation skills, a component of spatial visualisation ability, could also be the cause for the lack of gain in mental rotation. For example, although it was expected that the subjects should be able to predict changes in the perspective view upon rotation of an object, subjects were not instructed to observe these changes during training. For example, during the sketching exercise, they were not asked to draw views of objects other than those seen from the standard views.

Thirdly, lack of gain could also be due to lack of mastery of depth cues. According to Seddon and Eniaiyeju (1986), the ability to visualise the effects of rotation transformations on diagrams of 3-dimensional structures is dependent on mastery of depth cues, which are the relative size cue, overlap cue, foreshortened line cue and the distortion of angles cue. Depth cues were however, not taught in the study and only three depth cues, that is, the distortion of angle cue, the overlap cue and the foreshortened line cue were used for the test items. The relative size cue was not provided, as that would be inconsistent with the engineering drawing convention.

Lastly, the low instrument reliability must also be considered, as the reliability of this particular component of the spatial ability instrument is only 0.53.

LIMITATIONS

The study is a field study that attempted to investigate the inter-relationships between learning and psychological variables in an engineering educational setting and was the first of its kind in Malaysia (Education Planning and Research Division, 1999). Naturally, it was a complex and challenging piece of research to carry out and it was no great surprise to us that the limitations only became apparent as the research progressed. For example, the sample sizes were less than ideal for the factorial design method adopted for the data analysis. The impact of the small samples was made worse by the unequal sample sizes between the male and female samples. However, the unequal sample sizes were unavoidable as the study employed intact classes of students where the smaller proportion of females to males is typical in any civil engineering population.

The short duration provided for training on spatial skills was also less than ideal. It is expected that longer teaching and learning duration could resolve the questions on gender by enhancing the prospect of greater effect size.

CONCLUSION

This study set out to establish causal relationships between teaching and learning of spatial skills and spatial visualisation ability. Although the improvement in the components of the spatial visualisation ability was varied, with the largest gain being on the engineering drawing tasks and the least on the mental rotation tasks the study did show that spatial visualisation skills in general were improved after the teaching and learning activities. The finding was deemed educationally significant although the gain in skills for the experimental group was not large that is, 1.6 marks (5.8%) higher than the control group. This gain highlights the role of concrete spatial activities in the development of spatial visualisation ability in engineering students. May be, more concrete activities should be provided to engineering students to give them the basis for imagination, as what one does not see or experience one cannot imagine.

More importantly, if spatial visualisation ability is accepted as being important to problem solving and learning in engineering, engineering educators need to place more emphasis on the development of these skills in their engineering students. For example, spatial skills training should be integrated across the curriculum, which would increase students' awareness of its importance thus optimising the conditions for positive skills transfer. Remedial lessons should also be made available to those who have poor spatial visualisation ability as normally practised with those who are weak in the mathematical and analytical skills.

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