An Investigation into Problem Solving Approaches Adopted During Graphical Reasoning Episodes

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Abstract

A core aim of contemporary design and technology education is the development of transferable and robust problem solving skills. Graphical education is a critical component in achieving this aim as it espouses to enhance students' problem solving skills by developing spatial ability through the inclusion of abstract visual problems. In addition to spatial reasoning, modelling is a critical competency associated with problem solving as it can support reasoning by facilitating discourse between a student and their conceptions.

A repeated cross-sectional study design was implemented to gather longitudinal data of student approaches to solving graphical reasoning problems. The study cohort consisted of two consecutive cohorts from Initial Technology Teacher Education (ITTE) programs who were selected based on their engagement in a graphical education module. A battery of psychometric tests of spatial ability was administered to each cohort as well as a selection of graphical tasks within a summative assessment designed to target a selection of cognitive faculties. The results of each measure were analysed through correlational analyses with problem solving strategies for one common graphical problem selected for further analysis.

The findings illustrate higher correlational significance between spatial ability and graphical performance in students with higher levels of spatial ability. A wider adoption of analytical methods and modelling strategies is seen in students with lower levels of spatial ability. Potential rationales are discussed for these findings concerning the adoption of analytical modelling methods and ecological rationality in the selection of problem solving approaches.

Introduction

The development of robust problem solving skills is among one of the most important focusses of contemporary education (Seery & Delahunty, 2015). The need to develop problem solving competencies is predicated by the constantly evolving nature of society in which students need to be equipped to negotiate. As society has advanced into the conceptual age (Pink, 2005) where ubiquitous access to pertinent information has become a reality, education systems need to respond by facilitating the development of cognitive flexibility and supporting fluidity in problem solving. As cultures become more visually orientated (Elkins, 2008), the role of graphical education in espousing visual reasoning capacities becomes increasingly significant, with two of the more prominent capacities meriting development in this domain being internal reasoning and external modelling.

Visual Reasoning

Reasoning to solve graphical or visual problems can involve a wide variety of specific reasoning styles. These include among others spatial reasoning, analytical reasoning and geometric reasoning (Linn & Petersen, 1985; Pittalis & Christou, 2010). Graphical education is differentiated within technology education by its unique aim in aspiring to develop visuospatial skills (DES, 2007) and it does this through engaging students in a range of visually orientated problems. These problems implicitly suggest the adoption of a spatial reasoning strategy as they regularly include abstract visual stimuli (Seery, Lynch, & Dunbar, 2011) however there is general consensus that both spatial and analytical reasoning are the two primary types of reasoning involved in spatial tasks (Bodner & Guay, 1997). This would suggest that graphical reasoning predominantly involves either spatial or analytical reasoning or a combination of both. A number of correlational studies have identified a link between spatial ability and performance in graphical education (e.g. Maeda, Yoon, Kim-Kang, & Imbrie, 2013; Sorby, 1999) further suggesting the significance of the role of spatial reasoning during graphical problem solving episodes. However, the associated etiological underpinnings are not well understood. Regarding the adoption of particular styles of reasoning, Linn and Petersen (1985) identified females as preferring analytical approaches with males preferring more holistic spatial approaches to posited spatial tasks. With females regularly cited as having lower levels of spatial ability to males (e.g. Sorby, 2009), the selection of analytical approaches to graphical problems may allude to underdeveloped spatial skills relative to the cognitive load imposed by the problem.

Modelling

Where reasoning capacities are underdeveloped, students can externally model information to provide support when problem solving. Kelly, Kimbell, Patterson, Saxton, and Stables (1987) eloquently describe the interaction between cognitive and external modelling through their dialectic model of the interaction of Mind and Hand. The relationship between modelling and reasoning is interconnected as while modelling can support or alleviate the need to reason, the need can also arise to reason about or while creating the model. Archer (1992a, p.6) defines cognitive modelling as "the basic process by which the human mind construes sense experience to build a coherent conception of external reality and constructs further conceptions of memory and imagination". Archer (1992b, p.7) more generally describes a model as "anything which represents anything else for informational, experimental, evaluative or communicative purposes". Therefore the creation of a model is always intentional but its intent will vary to meet the idiosyncratic needs of its creator. Models do not need to be the "absolute best" (Koen, 1985, p.15) as there role in problem solving is typically to provide a mechanism to support the achievement of a solution. In the context of problem solving, modelling can therefore offer support in multiple forms. For example, the problem solver can create a model to overcome a deficit in cognitive resources at any stage of a given problem or to appraise a solution in whole or in part for confirmation or consolation.

Research Focus

Developing graphical problem solving skills to facilitate flexibility in problem solving is of paramount importance. These skills afford students a wide variety of cognitive tools to support fluidity in the conceptualisation of problem solving approaches. Therefore, this study aimed to explore the potential link between spatial ability and graphical reasoning to examine the utilisation of this capacity. It also sought to investigate student approaches to solving graphical problems with a particular focus on any potential modelling methods adopted by students.

Method

Approach and Participants

A repeated cross-sectional study design was implemented to gather longitudinal data of student approaches to solving graphical reasoning problems. The study was conducted across two cohorts of students in their 3rd year of an Initial Technology Teacher Education (ITTE) program while they were engaging in a Design and Communication Graphics (DCG) module. The cohorts came from consecutive years, 2014 (N=112) and 2015 (N=103). The students were selected for this study as the graphics module they were engaging with aimed to develop reasoning styles pertinent to solving graphical problems such as spatial and analytical reasoning. The concurrent focus on multiple approaches to problem solving also suggested the appropriateness of these students to participate in this study.

Throughout the module the students completed a variety of psychometric tests designed to measure different spatial factors and as well as a variety of graphical reasoning problems contextualised as an element of a summative examination. Within the library of graphical problems a number of cognitive faculties were targeted, in particular visual processing and domain-specific knowledge (Schneider & McGrew, 2012). Performance in these tasks were subsequently analysed to gain insight into the students' reasoning styles and problem solving approaches.

Design and Implementation

One aim of the study was to examine the potential link between spatial reasoning capacities and problem solving approaches when solving graphical reasoning problems. To facilitate this, psychometric tests of spatial ability were administered to each cohort. For the 2014 cohort, the Purdue Spatial Visualisation Test: Visualisation of Rotations (PSVT:R) (Bodner & Guay, 1997) and the Mental Cutting Test (MCT) (CEEB, 1939) were selected. The PSVT:R is posited to measure the spatial relations factor or the capacity to mentally rotate complex three-dimensional geometries and the MCT is posited to measure the visualisation factor, a general factor of spatial ability describing the universal ability to mentally manipulate visual stimuli. For the 2015 cohort, the PSVT:R was utilised to allow a common measure across cohorts. The MCT was replaced with an adapted Object Perspective Taking Test (OPTT) (Hegarty & Waller, 2004) and the Card Rotations Test (CRT) (Ekstrom, French, Harman, & Derman, 1976). The OPTT measures spatial orientation, a spatial factor describing the capacity to take a different cognitive perspective in space to achieve an additional perspective of a visual stimulus. The CRT measures the speeded rotation factor or the capacity to mentally rotate two-dimensional geometries quickly. The adaption to the OPTT was necessary due to a lack of access to the original test. The adapted test was designed to utilise the exact stimulus and item design as in the original test.

A battery of graphical reasoning problems was also administered to the participants as an element of a summative assessment. Each cohort received a different selection of tasks differentiated only by geometry manipulation while pertinent domain-specific knowledge remained identical. The tasks were designed to encourage a principles based approach to solving the problems to facilitate a degree of flexibility within the solutions. All problems were included in an initial correlational analysis with the students' performance in the spatial ability tests. Following this, one problem which was included for both cohorts with only a minor variation was selected for a more detailed analysis (see Figure 1). This problem was selected as it was a general task where no domain-specific knowledge was required. The task suggested a spatial reasoning approach however it is acknowledged that various modelling strategies and analytical methods could be implemented for support or to audit.

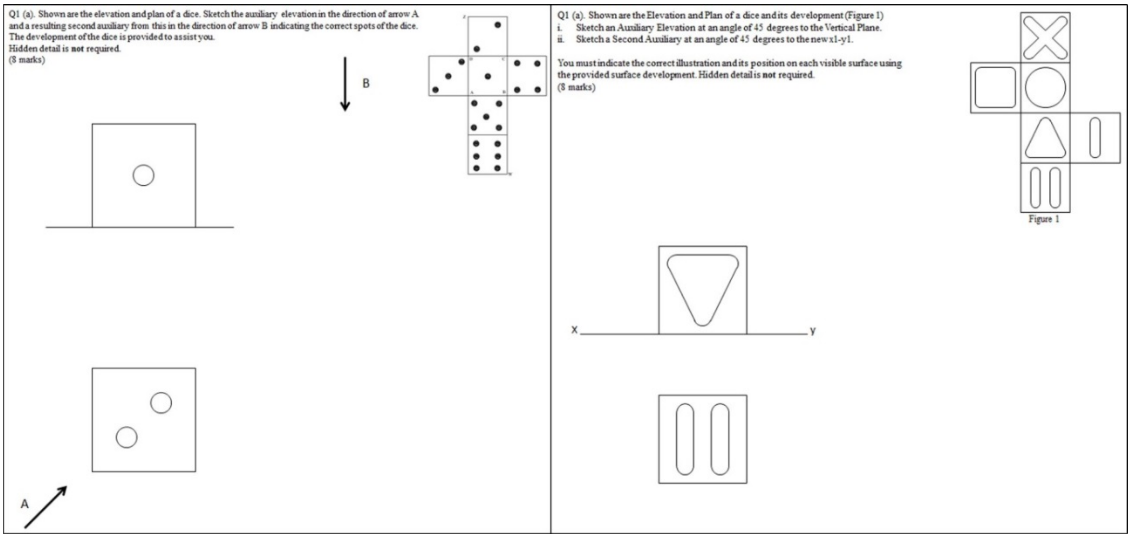

Figure 1: 2014 graphical problem (left) and 2015 graphical problem (right) for case study analysis

The solution to the problem is divided into two parts, the creation of an auxiliary elevation and a subsequent second auxiliary in the directions of the arrows presented in the 2014 problem. Each of these parts was hypothesized to consist of two elements, the identification of the resulting cube and the identification of the correct surface illustrations. The solution for the 2014 problem is illustrated in Figure 2. The only variation in problems between cohorts was that the 2014 problem had surface illustrations modelled after a dice and the 2015 problem replaced these with geometric figures.

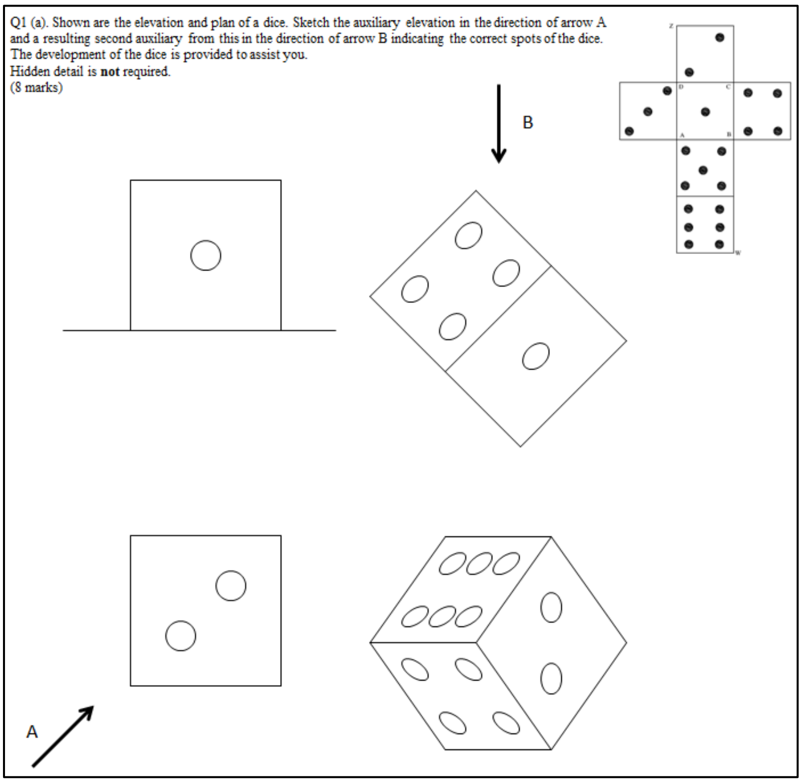

Figure 2: Solution to the 2014 graphical problem

Findings

A correlational analysis was conducted between performance in the psychometric tests and performance in the graphical reasoning problems. The results of this analysis are presented in Table 1. The graphical problems are coded such that problem A1_Cube_Aux_1 refers to problem A part 1 which involves identifying the 1st auxiliary view of a cube.

Table 1: Correlation matrix for scores on psychometric spatial ability tests and performance in graphical reasoning problems

2014 Cohort

		PSVT:R	MCT
PSVT:R	Pearson Correlation	1	.530**
	Sig. (2-tailed)		.000
	N	95	85
MCT	Pearson Correlation	.530**	1
	Sig. (2-tailed)	.000	
	N	85	88
A1_Cube_Aux_1	Pearson Correlation	-.078	-.047
	Sig. (2-tailed)	.450	.667
	N	95	88
A2_Cube_Aux_2	Pearson Correlation	.312**	.413**
	Sig. (2-tailed)	.005	.000
	N	79	74
B1_Plane_Traces	Pearson Correlation	.070	.187
	Sig. (2-tailed)	.620	.188
	N	52	51
C1_Boolean_Modelling	Pearson Correlation	.018	.221
	Sig. (2-tailed)	.878	.062
	N	73	72
C2_Bi_Directional_Associativity	Pearson Correlation	-.050	.102
	Sig. (2-tailed)	.696	.443
	N	63	59
D1_Double_Hyperbola	Pearson Correlation	.139	.072
	Sig. (2-tailed)	.239	.557
	N	74	68
D2_Eccentricity	Pearson Correlation	.115	.201
	Sig. (2-tailed)	.293	.075
	N	85	79
E1_Lamina	Pearson Correlation	.391**	.449**
	Sig. (2-tailed)	.000	.000
	N	85	78
E2_Lamina	Pearson Correlation	.260	.327*
	Sig. (2-tailed)	.065	.025
	N	51	47
F1_Skew_Lines	Pearson Correlation	-.108	.008
	Sig. (2-tailed)	.366	.947
	N	72	67
G1_Tetrahedron	Pearson Correlation	.188	.498**
	Sig. (2-tailed)	.140	.000
	N	63	58
H1_Ellipse	Pearson Correlation	.143	.215
	Sig. (2-tailed)	.184	.053
	N	88	81
H2_Parabola	Pearson Correlation	.274	.087
	Sig. (2-tailed)	.059	.583
	N	48	42
I1_Cube_Tetrahedron	Pearson Correlation	.306*	.491**
	Sig. (2-tailed)	.014	.000
	N	64	57
J1_Pyramid_Intersection	Pearson Correlation	.276*	.311*
	Sig. (2-tailed)	.027	.013
	N	64	63
J2_Prism_Intersection	Pearson Correlation	.225	.362**
	Sig. (2-tailed)	.053	.002
	N	75	71
K1_Development_Envelopment	Pearson Correlation	. 305**	.357**
	Sig. (2-tailed)	.007	.002
	N	77	72

2015 Cohort

		PSVT:R	OPTT	CRT
PSVT:R	Pearson Correlation	1	.256*	.369**
	Sig. (2-tailed)		.016	.000
	N	89	88	89
OPTT	Pearson Correlation	.256*	1	.261*
	Sig. (2-tailed)	.016		.014
	N	88	88	88
CRT	Pearson Correlation	.369**	.261*	1
	Sig. (2-tailed)	.000	.014	
	N	89	88	89
A1_Cube_Aux_1	Pearson Correlation	.030	.041	-.081
	Sig. (2-tailed)	.780	.707	.452
	N	89	88	89
A2_Cube_Aux_2	Pearson Correlation	.173	-.036	.046
	Sig. (2-tailed)	.113	.748	.675
	N	85	84	85
B1_Plane_Traces	Pearson Correlation	.004	.163	.028
	Sig. (2-tailed)	.972	.142	.801
	N	84	83	84
C1_CAD_Modelling	Pearson Correlation	.076	.314**	.078
	Sig. (2-tailed)	.519	.006	.504
	N	75	74	75
C2_CAD_Systems	Pearson Correlation	.065	.086	.104
	Sig. (2-tailed)	.623	.515	.428
	N	60	60	60
D1_Parabola	Pearson Correlation	-.038	.048	.112
	Sig. (2-tailed)	.732	.666	.316
	N	83	82	83
D2_Parabola_Tangent	Pearson Correlation	.006	.055	.206
	Sig. (2-tailed)	.960	.615	.055
	N	87	86	87
E1_Plane_Traces	Pearson Correlation	.102	-.053	.005
	Sig. (2-tailed)	.417	.676	.966
	N	66	65	66
F1_Skew_Lines	Pearson Correlation	-.011	.161	.107
	Sig. (2-tailed)	.920	.159	.348
	N	79	78	79
F2_Plane_Traces	Pearson Correlation	.222	.081	.055
	Sig. (2-tailed)	.071	.519	.661
	N	67	66	67
G1_Tetrahedron	Pearson Correlation	.058	.097	.082
	Sig. (2-tailed)	.632	.420	.498
	N	71	71	71
G2_Sphere_Contact	Pearson Correlation	.072	.235	.101
	Sig. (2-tailed)	.646	.133	.519
	N	43	42	43
H1_Hyperbola_Points	Pearson Correlation	.067	.044	-.153
	Sig. (2-tailed)	.615	.748	.251
	N	58	57	58
H2_Hyperbola_Curve	Pearson Correlation	.067	-.075	.009
	Sig. (2-tailed)	.688	.659	.958
	N	38	37	38
H3_Conic_Sections	Pearson Correlation	-.197	.045	.040
	Sig. (2-tailed)	.223	.784	.804
	N	40	39	40
I1_Compound_Pyramid	Pearson Correlation	.056	.153	.107
	Sig. (2-tailed)	.669	.243	.410
	N	61	60	61
I2_True_Shape	Pearson Correlation	-.240	-.076	-.165
	Sig. (2-tailed)	.113	.622	.277
	N	45	45	45
J1_Prism_Intersection	Pearson Correlation	-.209	.145	-.144
	Sig. (2-tailed)	.179	.352	.357
	N	43	43	43
J2_Octahedron_Intersectio	Pearson Correlation	-.124	-.150	.069
	Sig. (2-tailed)	.411	.319	.650
	N	46	46	46
K1_Development	Pearson Correlation	-.056	-.088	-.021
	Sig. (2-tailed)	.618	.437	.849
	N	81	80	81

K2_Envelopment	Pearson Correlation	.137	.024	-.034
	Sig. (2-tailed)	.249	.838	.777
	N	73	73	73
K3_Origami	Pearson Correlation	-.020	-.174	.082
	Sig. (2-tailed)	.894	.253	.594
	N	45	45	45

**. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed).

The results indicate very few statistically significant correlations between the spatial tests and performance in the graphical reasoning problems. No significant correlation between a spatial test and graphical problem exceeded an *r* value of .5 with correlations ranging to low (*r* = .276) to moderate (*r* = .498).

To gain additional insight into the problem solving strategies adopted by the participants', further analysis was conducted into the solutions of the one of the graphical reasoning problems as discussed earlier. The approach deemed most appropriate was to separate the participants into quartiles based on their scores in the PSVT:R. An independent-samples t-test was conducted to compare the mean PSVT:R scores between the two cohorts to identify if their results could be combined prior to identifying quartile values. There was not a statistically significant difference in the scores for 2014 cohort (*M* = 76.42, *SD* = 14.90) and 2015 cohort (*M* = 77.86, *SD* = 13.89), t (185) = -.684, p = .495. A chi-square test of independence was subsequently performed to examine the relationship between participants being in a specific cohort and being in a specific quartile. The relationship between these variables was not significant, χ^2 (3, n = 170) = 1.02, p = .797. These results show no evidence of a relationship between cohorts and quartiles and therefore suggest the consideration of all participants as a single cohort was acceptable. Figure 3 illustrates the results of the analysis of all participants PSVT:R results. The boxplot identifies the quartile values (Q1 = 70, Q2 = 76.67, Q3 = 90, Q4 = 100) and the histogram identifies the frequency of the scores achieved by each student.

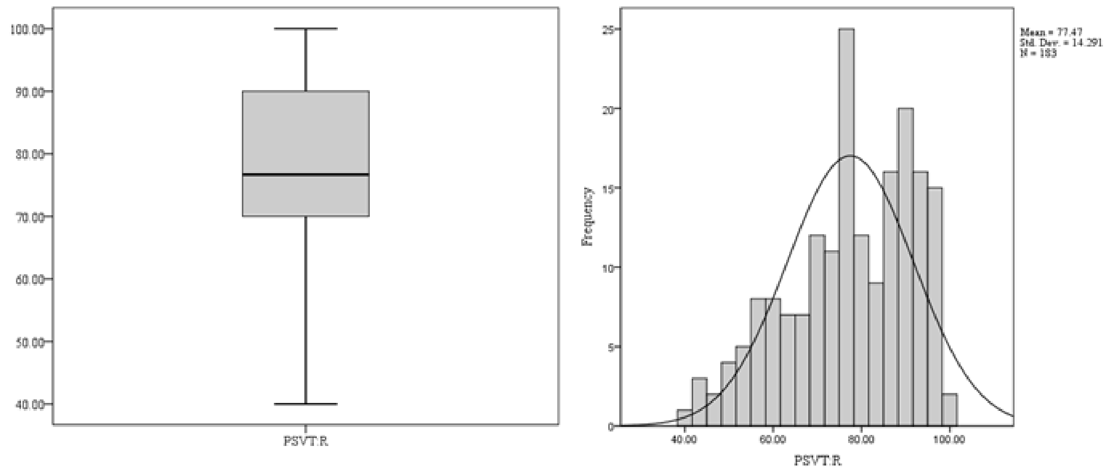

Figure 3: Boxplot (left) to identify quartile values and histogram (right) to identify frequencies of results in the PSVT:R

After identifying the quartiles associated with performance in the PSVT:R, it was determined appropriate to identify if there was any variance in performance in the graphical task across each quartile. The mean performance was calculated for each group and the results are presented in Figure 4. A trend emerged which illustrates that in general, participants with a higher score in the PSVT:R performed better in the graphical task. While there is only a marginal difference between the 2nd and 3rd quartiles, the difference is more prominent between the 1st and 4th. An independent-samples t-test was then conducted to compare the mean performance scores in the graphical problem between the 1st and 4th quartiles as these groups exhibited the highest degree of variance. The results showed no statistically significant difference between the scores for participants in the 1st quartile (*M* = 68.45, *SD* = 22.15) and in the 4th quartile (*M* = 74.79, *SD* = 23.84), *t* (86.858) = -1.299, *p* = .197. Despite the lack of statistical significance, the emergent trend merits further exploration in relation to the strategies utilised within each quartile.

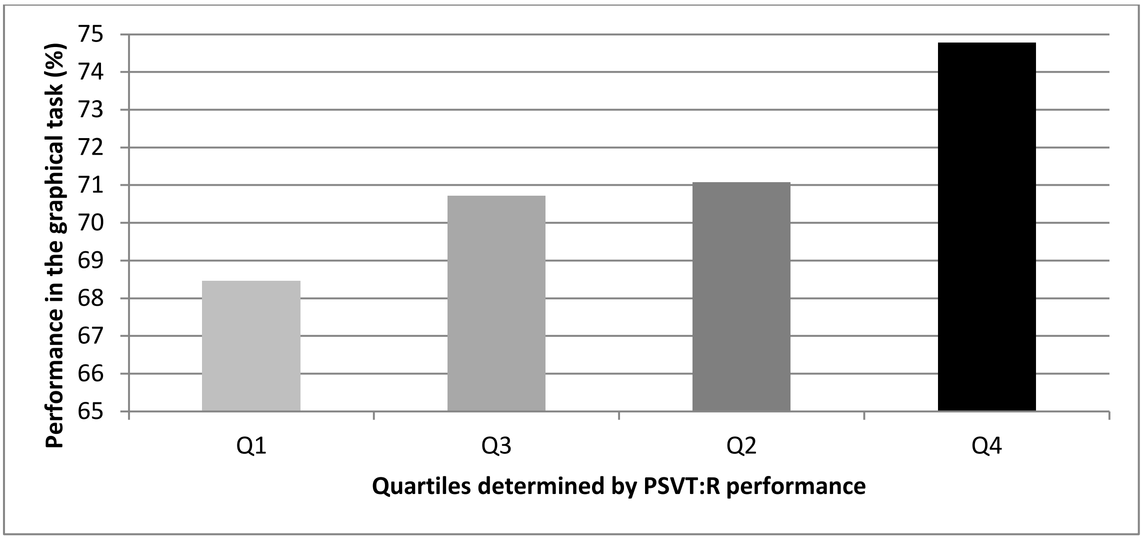

Figure 4: Performance in the graphical task across all quartiles

The next stage of the analysis sought to identify if there was a correlation between the PSVT:R and performance in a specific common graphical problem as previously discussed. The results are shown in Table 2 and indicate that the significance in the correlations increase as the quartiles progress towards the Q1 with the only statistically significant correlations being in the 4th quartile. This would suggest the adoption of a holistic spatial approach as primarily occurring with the participants who had a higher capacity in this reasoning style.

Table 2: Correlations between performance in both parts of the graphical reasoning problem and PSVT:R scores for participants in each quartile

		A1_Cube_Aux_1	A2_Cube_Aux_2
Q1_PSVT:R	Pearson Correlation	-.223	-0.11
	Sig. (2-tailed)	.142	.944
	N	45	45
Q2_PSVT:R	Pearson Correlation	.219	.184
	Sig. (2-tailed)	.316	.401
	N	23	23
Q3_PSVT:R	Pearson Correlation	.179	.186
	Sig. (2-tailed)	.163	.148
	N	62	62
Q4_PSVT:R	Pearson Correlation	.285*	.326*
	Sig. (2-tailed)	.038	.017
	N	53	53

*. Correlation is significant at the 0.05 level (2-tailed).

In order to examine the strategies adopted in solving the graphical problem, the participants' solutions were coded into methods and modelling techniques which were deduced from an observational analysis of their solutions. These methods, depending on their nature, can offer insight into the efficacy of the cognitive models generated by the students. The solutions illustrated varying strategies to solving the problem both in terms of the nature and quantity of the methods adopted. The resulting methods and descriptions are presented in Table 3.

Table 3: Descriptions of methods and modelling techniques adopted in solving the graphical problems

Method	Description
Adapted Development	Adapting the provided development
Indexing	Indexing the vertices of the cube
Isometric Sketch	Creating an isometric sketch of the cube
Additional Orthographic Information	Illustrating additional surface illustrations in the given orthographic views
Hidden Detail	Adding hidden detail (not required) in their solutions
Illustrations Converted to Numbers	Converting the surface illustrations to numerical figures

To examine the participants' strategies to solving the problems, relationships between each quartile and the problem solving approaches were analysed using a series of Chi-square tests. No test identified any statistical significance between the quartiles and methods however a number of trends were revealed from the analysis.

Figure 5 illustrates the number of methods utilised by participants across quartiles. Of particular interest are the 1st and 4th quartiles. Of all the participants that didn't use any supporting method, 21.1% were in the 1st quartile and 38.6% were in the 4th quartile. Of all the participants that used a combination of 3, 50% were in the 1st quartile and 16.7% were in the 4th quartile. From within these two quartiles, 28.6% of quartile 1 didn't utilise any supporting method while 14.3% utilised a combination of 3 and 46.8% of quartile 4 didn't use any while 4.3% used a combination of 3. This suggests a higher dependency on externalising techniques by the participants in the 1st quartile suggesting either a lower efficacy in their cognitive models or a lower capacity to interact with these models.

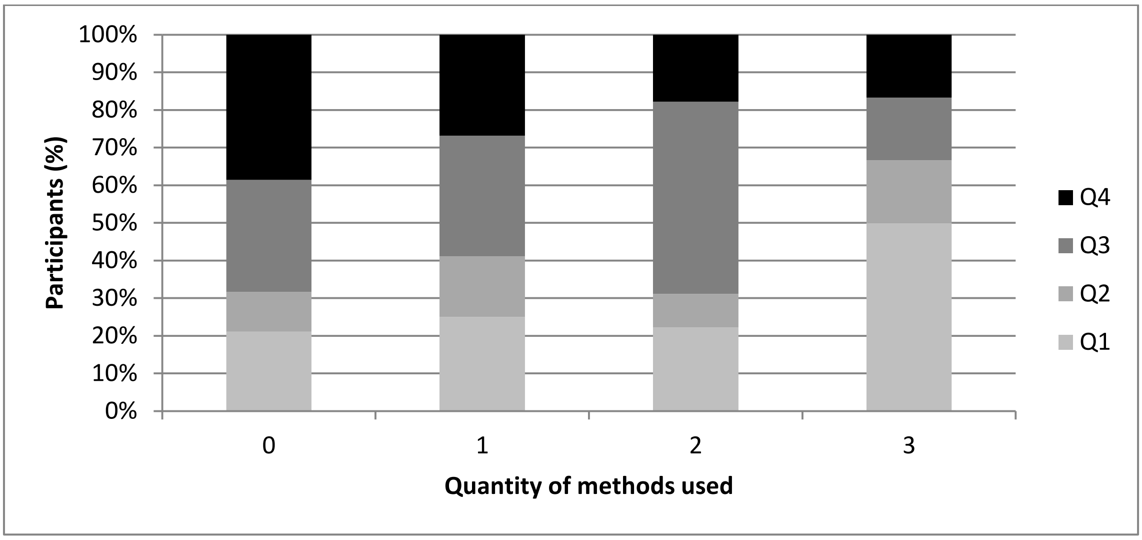

Figure 5: Number of modelling techniques utilised across quartiles

The results of further analysis between the 1st and 4th quartiles in relation to the graphical methods adopted are illustrated in Figure 6. With the exception of adding additional information to the provided orthographic views, each method was used more in the 1st quartile than in the 4th. The largest variances can be seen in the creation of an isometric sketch [23.8%], indexing [11.7%] and adapting the development [7.6%]. This is of particular interest as it is arguable as these techniques most support the assistance or circumvention of spatial reasoning by alleviating the need to maintain a vivid cognitive model of the geometry.

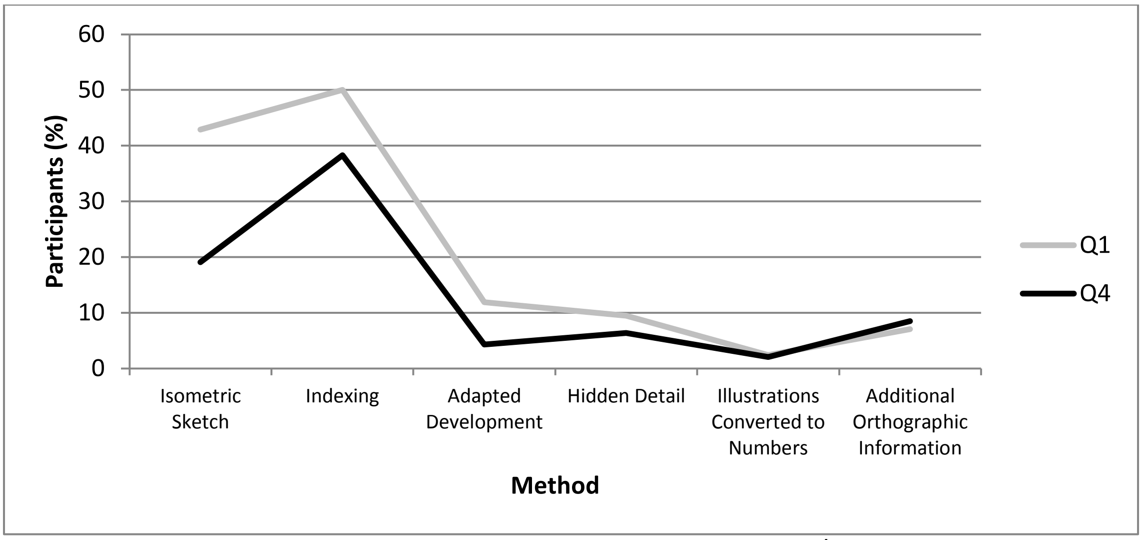

Figure 6: Graphical methods utilised by participants in the 1st and 4th quartiles

Discussion

The findings illustrate that the students who resided in higher quartiles in relation to their level of spatial ability performed better in the graphical tasks and also evidenced a higher dependency of cognitive modelling rather than external or analytical methods. These results align with previous correlational studies which suggests a link between spatial ability and performance in graphical education (Maeda et al., 2013; Sorby, 1999). In the classical theory of problem solving it is theorised that framing a problem involves building a mental representation of its structure known as the *problem space* (Newell & Simon, 1972). Based on the results of this study it is posited that the increased capacity to manipulate a conception within this problem space resulted both in the adoption of more holistic spatial approaches and consequential superior performance in the graphical tasks. The increased efficacy in students' cognitive models for those with higher spatial reasoning capacities resulted in a lower number of instances where an intent to externally model emerged.

With respect to the wider educational agenda of design and technology education where problem-based learning (PBL) is a pedagogical approach characteristic of the discipline, increasing spatial skills has the potential to contribute to the development of cognitive flexibility and an increased fluidity in problem solving approaches. Each student exists within a unique bounded rationality while they engage with a problem in that their decisions are governed by time, information and cognitive computational capacities (Gigerenzer & Goldstein, 1996). Within the problem solving episode the time is task dependant and the information is situated but the cognitive capacities are, in some instances, unbounded. Increasing cognitive capacities within students can offer potentially limitless scope for interactions with thoughts and ideas due to the unbounded realm of the mind which is in direct contrast to limitations which exist in the physical manifestation of a task environment.

However, the human mind is not completely unbounded and cognitive capacities are not entirely limitless. The problem solving space offered within the mind for cognitive modelling is analogous to the dimensionless properties of virtual modelling environments but access to cognitive resources to operate within this space is restricted. Working memory is a particular cognitive competency associated with mental operations and has a restricted capacity (Cowan, 2001;

Miller, 1956). Considering Johnston-Wilder and Mason's (2005) model for effective learning (Figure 7), these cognitive limitations can impede on the manipulation phase. In these circumstances, the creation of physical models can alleviate the cognitive deficits associated with storing the cognitive model. As such, while developing cognitive modelling skills can contribute to problem solving, a critical skill emerges in determining when it is ecologically rational to externalise thoughts and ideas to maintain a fluid discourse for the student with their ideas.

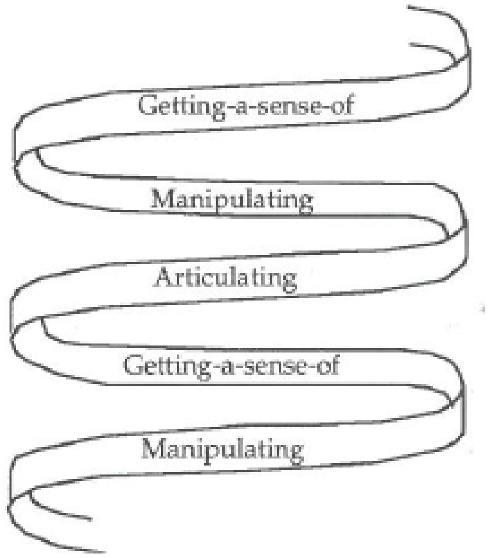

Figure 7: Model for effective learning (Johnston-Wilder & Mason, 2005)

Conclusion

The findings suggest that while engaging with graphical tasks, having an underdeveloped level of spatial ability may stimulate the need to incorporate external modelling techniques into problem solving strategies. It is posited that the creation of the model offers support by removing the need to maintain the cognitive model within the working memory thus allowing more cognitive resources to be allocated to solving the posed problem. Design and technology education is ideally situated to develop both internal and external modelling skills in authentic and meaningful environments. In this study, the findings illustrate that having lower levels of spatial ability resulted in a need to 'think externally' during the problem. For these students, while not implicit within the task, it is likely this was the ecologically optimal solution. As these problems were characteristic of typical graphical problems which are designed to develop or assess spatial reasoning, this raises concerns pertinent to the efficacy of graphical tasks for this purpose. Multiple other cognitive faculties are likely to load on tasks designed to facilitate problem solving development such as processing speed, fluid reasoning and short-term memory (Schneider & McGrew, 2012). Stemming from this study further research is warranted to identify the ecological intent underpinning the use of models relative to the cognitive faculties suggested and employed. An increased understanding into how and why modelling is utilised in association with such faculties would support the development of pedagogical strategies which focus on the development of robust and flexible problem solving skills.

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