Examining the Relationship Between Spatial Ability and Cognitive Load During Complex Problem Solving

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Abstract

Spatial ability is documented as a predictor of success in STEM disciplines and noted to contribute to individuals problem-solving approaches. While there is a significant body of correlational evidence indicating that spatial ability relates to success in different areas in STEM, there is a gap in understanding of the cause of this relationship. The work presented through this paper seeks to contribute towards addressing this gap. Spatial ability is outlined as a cognitive factor through theories of intelligence. Thus, it is theorised through this research that spatial ability's contribution to complex problem solving may be due to the management of cognitive resources. To evaluate this theory, this paper seeks to explore whether individuals with higher levels of spatial ability have a greater capacity to manage cognitive resources while solving problems, therefore reducing the cognitive load experienced.

Undergraduate engineering students in their first (n = 114) and third (n = 79) year of study were invited to participate in the research. Participants were asked to solve the three-disk and more difficult four-disk Tower of Hanoi problem, which are representative of a complex problem. Following the completion of each problem a 9-point Likert-type item was administered to measure cognitive load. Three psychometric spatial tests were administered to participants, The Purdue Spatial Visualization Test and Rotations/Mental Rotation Test-A, Surface Development Test, and Paper Folding Test.

Through analysis of the data a significant relationship was found between spatial ability and problem-solving performance, where higher levels of spatial ability related to improved performance. A significant relationship was also found between spatial ability and the cognitive load experienced during problem solving, where higher levels of spatial ability related to lower levels of cognitive load. These findings suggest that higher levels of spatial ability support the management of cognitive resources during problem solving. The findings are discussed in relation to the existing body of research and potential avenues for future work are explored.

Key Words: Spatial ability, Problem solving, Cognitive load, STEM education.

1. INTRODUCTION

Throughout the last number of years, a significant body of research has demonstrated that spatial ability is a predictor of success of individuals in Science, Technology, Engineering and Mathematics (STEM) disciplines (Kell & Lubinski, 2013; Lubinski, 2010; Sorby et al., 2018; Sorby & Veurink, 2019; Stieff & Uttal, 2015; Uttal et al., 2013; Uttal & Cohen, 2012; Wai et al., 2009). Aligning more than 50 years of research on spatial ability in STEM disciplines, Wai et al. (2009) demonstrated that individuals with higher levels of spatial ability are more likely to pursue studies in STEM fields and achieve advanced degrees i.e., bachelors, masters, and PhDs. Further to this, research has also indicated that spatial ability relates to the underrepresentation of cohorts in STEM (Ball et al., 2019; Blums et al., 2017; Sorby & Veurink, 2019; Wang & Degol, 2017). Considering these factors, research has evolved to focus on how spatial ability relates to performance in STEM fields. Research has included explorations of the malleability of spatial skills, spatial training interventions, and the relation of spatial ability to success in solving various types of problems (Buckley et al., 2019; Casey et al., 2017; Lowrie et al., 2019; Sorby & Veurink, 2019; Stieff & Uttal, 2015; Uttal, Meadow, et al., 2013) . While research continues to examine how spatial ability relates to success in STEM, it is also necessary to work towards understanding why spatial ability relates to performance in these disciplines. This research aims to contribute towards understanding why spatial ability relates to success in problem solving, a significant component of STEM practice, by exploring this relationship from a cognitive perspective. As spatial ability is a cognitive factor (Schneider & McGrew, 2018), this work posits that it may relate to the levels of cognitive load experienced by learners when engaging in problem-solving experiences. Should a relationship be identified between spatial ability and cognitive load in problem solving, it would not only serve to advance understanding of why spatial ability relates to success in STEM. This could also inform a means for educators to support students in managing cognitive load, which can influence learners in achieving learning goals (Sweller et al., 2011), during problem-solving educational experiences.

2. BACKGROUND

2.1. Spatial ability and problem solving

Within the most extensive contemporary theory of intelligence, the Cattell-Horn-Carroll (CHC) theory, spatial ability is classified as one of sixteen broad cognitive factors which contribute to the structure of an individual's general intelligence (Schneider & McGrew, 2018). Through this theory, spatial ability is described as "the ability to make use of simulated mental imagery to solve problems - perceiving, discriminating, manipulating, and recalling non-linguistic images in the "mind's eye"" (Schneider & McGrew, 2018, p. 125). Problem solving is a significant component of STEM disciplines and solving problems in these disciplines often requires individuals to reason about spatial information (Stieff & Uttal, 2015). Given the varying structures of problems in STEM, from ill-defined design problems to complex well-defined problems requiring a specific solution, spatial ability's role in problem solving may vary when solving different types of problems (Reid et al., 2018). Research has also moved to explore the different problem-solving approaches of students with various levels of spatial ability. Studies in this space have demonstrated that higher visualisers show a more holistic approach to problem solving, whereas lower visualisers may use 'piecemeal' or analytic strategies to solve problems (Khooshabeh et al., 2011; Lin, 2016; Tzuriel & Egozi, 2010). Holistic approaches to problem solving are outlined as being more efficient than analytic or 'piecemeal' strategies used by lower visualisers (Tzuriel & Egozi, 2010).

As problem solving is a core component in STEM practice, it is important that STEM education emphasises the development of students' capacity to employ these more efficient holistic problem-solving strategies. Spatial skills are malleable (Sorby et al., 2018; Sorby et al., 2013; Stieff & Uttal, 2015; Uttal, Meadow, et al., 2013), therefore advancing these skills throughout education may support STEM students in developing holistic problem-solving capability. However, it is also necessary to understand why spatial ability supports the use of more holistic problem-solving approaches. This may be due to higher visualisers having more cognitive resources available to build referential connections between different types of information representations e.g., verbal, and visual (Mayer & Sims, 1994). If this is the case, this could be reflected in the cognitive load experienced during problem solving.

2.2. Cognitive load

Cognitive load relates to the total working memory resources required to carry out a learning activity (P. A. Kirschner et al., 2018) . Cognitive load theory seeks to explain how the load placed on an individual's capacity to process information during learning experiences can influence their ability to effectively learn and process new information (Sweller et al., 2019) . The theory is based on the premise that individuals limited capacity to temporarily hold and process information, working memory capacity, can constrain their cognitive processing capacity therefore increasing cognitive load (Chen & Kalyuga, 2020; Sweller et al., 2019).

The goal in education is to facilitate learning and therefore it is necessary to optimise intrinsic cognitive load which is associated with the structure of the information that a learner needs to acquire (F. Kirschner et al., 2009; P. A. Kirschner et al., 2018). In situations where this load is not optimised, too much demand can be placed on working memory resources and hinder student's capacity to; learn, successfully perform a task, or willingness to engage in similar tasks in the future (Chen & Kalyuga, 2020; Sweller et al., 2011, 2019). It is theorised through this research that when problem solving, higher visualisers may have a greater capacity to optimise cognitive load than lower visualisers. Problem solving is initiated by constructing internal representations of the problem statement creating the "problem space" (Fischer et al., 2011). This research proposes that higher visualisers, by virtue of having increased visualisation capacity, may experience less difficulty in building the problem space and thus experience less cognitive load. Through experiencing less cognitive load, they may have more mental resources available to deal with the information they need to acquire and therefore have a greater possibility of successfully solving the problem and learning from the experience.

This theorised relationship between spatial ability and cognitive load during problem solving will be explored through this paper. The work aims to advance understanding of the cause of spatial abilities relationship to success in STEM disciplines. This study will specifically focus on investigating this relationship with engineering students engaging in a complex problem-solving activity.

3. METHOD

Undergraduate engineering students in the first (n = 114) and third (n = 79) year of their studies were invited to participate in the research. Participants were recruited through email, lecture visits, and notice board advertisements. An incentive of entry into a draw to win a Samsung Tablet was used. Ethical approval was sought and granted by the ethics committee at the institution. Details and records relating to participants were stored securely in line with institution guidelines for ethical handling and storage of data. Participant numbers were assigned to ensure participant anonymity. Participants were made aware that they were free to withdraw from the study at any time without providing reason and written consent was obtained.

Participants in the research were scheduled to take part in two sessions. In the first session, participants completed two complex problems and indicated the level of mental effort experienced when solving the problem. In the second session, participants completed a series of spatial tests to obtain a measure of spatial ability. Performance was then analysed across groups and correlation analysis conducted to examine the hypothesised relationship between spatial ability and cognitive load experienced during complex problem solving.

3.1. Implementation

In session one, the well-defined closed problem, the Tower of Hanoi (TOH) was administered. This represents a measure of complex problem-solving capability (Eielts et al., 2020; Schiff & Vakil, 2015) which is a key skill for performing in STEM. To solve the TOH, an individual is required to get the arrangement of disks on the left-most peg onto the right-most peg in the same order. There are two constraints for the problem solver; (1) only one disk can be moved at a time and (2) a larger disk cannot be placed on top of a smaller disk. Success in solving the problem is typically measured by the number of moves made and time taken to solve the problem. The TOH has previously been critiqued for being too simplistic, transparent, and static (Funke, 2010). However, the complexity of the problem is noted to lie within the identification and management of sub-goals, consideration for implications of actions and awareness of the need for counterintuitive moves to reach the goal state (Schiff & Vakil, 2015).

In this session participants were administered the three-disk and more difficult four-disk version of the TOH. Initially participants were presented with the three-disk problem and the instructions for the task explained. They were then asked to begin the problem, represented in Figure 1 below. Participants engagement with the problem was audio and video recorded to facilitate retrospective evaluation of performance. Once a participant had completed the problem, they were asked to indicate on a 9-point Likert-type item the amount of mental effort, representative of overall cognitive load experienced (Paas, 1992), they experienced solving the problem. Upon completion of this, the more difficult four-disk TOH problem was administered and when completed participants were again asked to indicate the amount of mental effort they experience on the Likert-type item.

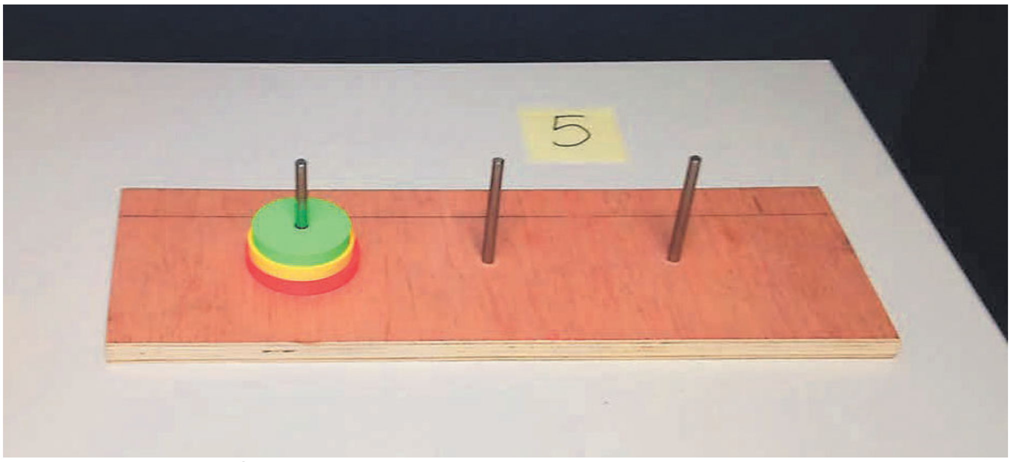

Figure 7. Three-disk TOH problem physical setup

In the second session, a series of spatial tests loading on the narrow cognitive factor of visualisation were administered. Visualisation is commonly used as a proxy measure for the broad cognitive factor of spatial ability (Buckley, 2020; Schneider & McGrew, 2018). Measuring a narrow cognitive factor, like visualisation, requires the use of multiple tests specific to the factor as using one test in isolation would represent an imperfect measure of the factor (Schneider & McGrew, 2018). Thus, the Purdue Spatial Visualisation Test (PSVT:R) (Bodner & Guay, 1997)/Mental Rotation Test-A (MRT-A) (Peters et al., 1995), Surface Development Test (SDT) and Paper Folding Test (PFT) (Ekstrom et al., 1976) were used to obtain a measure of visualisation. These tests are commonly used to measure spatial visualisation in research. The PSVT:R (a 30-item test) requires individuals to mentally rotate a shape into a position though the same rotation as an example shape and select the correct answer from five possible options. The MRT-A is a 24-item two-part test which requires the individual to identify which two images of four possible options represent the same shape rotated into two different positions. The SDT is a two-part 12-item test requiring individuals to visualise how a piece of paper may be folded to form an object. The individual is then required to match the lettered edges of the piece of paper to the numbered edges of the object. The PFT is a 20-item two-part test where an individual must imagine a piece of paper being folded, a hole punched, unfolded, and identify where the holes in the paper would appear. The order of the tests was randomised across participants to support analysis considering test fatigue.

4. RESULTS

The data collected was initially compiled in Microsoft Excel before cleaning and analysing in R Studio (R version 4.1.0.) and IBM SPSS (Statistics 27).

4.1. Data cleaning and pre-processing

Of the participants that completed the spatial tests, 18 completed the MRT-A in place of the PSVT:R as these participants were taking part in another spatial study. These 18 participants MRT-A scores were merged with the PSVT:R scores as through previous research a significant correlation of very large effect size has been demonstrated between performance on the two tests ($r = 0.621$, $p < 0.001$) (Schmidt et al., 2020). To correct for the PSVT:R and MRT-A having a different number of items, participants scores were converted to percentages before they were merged as a means of standardisation. Participants scores on the SDT and PFT were also converted to percentages for consistency. Scores on each test were then transformed into z-scores and a composite z-score taken as the average across the three spatial test scores. This is similar to the process implemented by Hambrick et al., (2012) when investigating spatial ability in scientific problem solving.

Having determined a composite spatial score, univariate outliers for all variables in the study were identified (see Table 1) and transformed to the upper and lower limits of respective variables using R Studio.

Table 10. Identification of univariate outliers

	Univariate outliers in variables	
Variable	**Univariate outliers**	**% of the data**
Spatial ability	1	0.56
Three-disk moves	5	2.82
Three-disk time	14	10.21
Four-disk moves	10	5.95
Four-disk time	12	8.76

4.2. Analysis

4.2.1. Performance and expertise

Initially descriptive statistics were determined for the number of moves made to solve the two complex problems, represented in Table 2 below. The minimum number of moves to solve the three-disk problem is 7 and for the four-disk problem is 15. As the mean number of moves for both first (M = 9.59) and third year (M = 10.50) students was close to the minimum number of moves for the three-disk problem a ceiling effect was investigated. This demonstrated that there was a ceiling effect with the three-disk problem and thus it was removed from further analysis.

Table 2. Descriptive statistics for moves made at different levels of engineering expertise

	Y	**N**	**M**	**SD**	**Med**	**Min**	**Max**	**Skew**	**Kurt**
Three-disk moves	1	107	9.59	3.88	8	7	26	2.16	5.42
	3	70	10.50	4.05	9.5	7	26	1.67	3.78
Four-disk moves	1	99	29.67	17.78	25	15	101	2.01	4.05
	3	69	32.49	18.13	27	15	96	1.51	2.11

Y = Year of study, N = sample size, M = Mean, SD = Standard deviation, Med = Median, Min = Minimum value, Max = Maximum value, Skew = Skewness, Kurt = Kurtosis

A Mann-Whitney U test was used to compare the performance of students on the four-disk problem across levels of expertise as the assumption of normality was violated. The results of this test indicated that there was not a statistically significant difference between performance on the four-disk problem (*U*= 2977.5, *p* > .05 (p= 0.1576), r = 0.09) with respect to engineering discipline expertise.

4.2.2. Spatial ability and performance

The analysis then proceeded to explore any potential relationship between spatial ability level and performance on the four-disk problem. A Spearman's rank correlation was conducted (see Table 3) which demonstrated a significant negative correlation between spatial ability and the number of moves to solve the problem r(155) = -.23, p = .033, and time taken to solve the problem r(135) = -.28, p = .022, with medium effect sizes. This suggests that as spatial ability increases, the number of moves to solve the problem and time taken to reach a solution decrease.

Table 3. Spearman correlation of complex problem-solving performance and spatial ability

Variable	**M**	**SD**	**1**	**2**
1. Spatial ability	0.01	0.83		
2. Moves	29.55	14.81	-.23** [-.38, -.08]	
3. Time	110.57	72.31	-.28** [-.43, -.11]	0.78*** [.70, .84]

p-value adjustment method: Holm (1979).
Observations: 137-155.
Note: **. Correlation is significant at the 0.01 level (two-tailed).
*. Correlation is significant at the 0.05 level (two-tailed).

4.2.3. Performance and cognitive load

Following the investigation of the relationship between spatial ability and performance, an analysis was carried out to explore a potential relationship between complex problem-solving performance and mental effort (overall cognitive load) experienced during problem solving. A Spearman's rank correlation was conducted (Table 4) which indicated significant positive correlations between mental effort and the number of moves to solve the problem (r(166) = .31, *p* < .001), with large effect size, and time taken to solve the problem (r(135) = .49, *p* < .001), with very large effect size. This suggests that as cognitive load increases the number of moves and time also increase, indicating poorer performance.

Table 4. Spearman correlation of complex problem-solving performance and mental effort

Variable	**M**	**SD**	**1**	**2**
1. Mental effort	4.72	1.67		
2. Moves	29.55	14.81	.31*** [.17, .45]	
3. Time	110.57	72.31	.49*** [.35, .61]	.78*** [.71, .84]

p-value adjustment method: Holm (1979).
Observations: 137-168.
Note: **. Correlation is significant at the 0.01 level (two-tailed).
*. Correlation is significant at the 0.05 level (two-tailed).

4.2.4. Spatial ability and cognitive load

The relationship between spatial ability and mental effort experienced during complex problem solving was then investigated through conducting a Spearman's rank correlation. Through this analysis, a significant negative correlation was determined between spatial ability and mental effort, (r(155) = -.18, *p* = .03), of small effect size. Thus, indicating that as spatial ability increases the cognitive load experienced during complex problem-solving decreases.

5. DISCUSSION

Through the data analysis for this study, significant relationships were identified between complex problem-solving performance, spatial ability, and cognitive load as depicted in Figure 2 below. Individuals with higher levels of spatial ability demonstrated greater levels of complex problem-solving capability, by virtue of solving the problem in less moves and time than individuals with lower levels of spatial ability. Therefore, indicating that higher visualisers were able to identify a more optimal solution to solving the problem. This aligns with existing research demonstrating that individuals with higher spatial ability employ more holistic problem-solving approaches, whereas individuals with lower levels of spatial ability may employ ‘piecemeal’ or analytic methods to solve a problem which are less optimal (Khooshabeh et al., 2011; Lin, 2016; Tzuriel & Egozi, 2010).

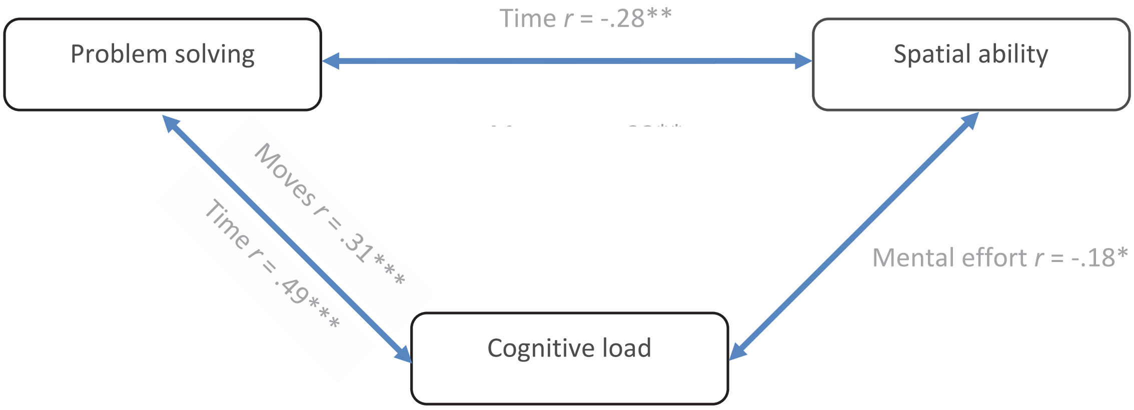

Figure 2. Relationships of significance identified between pertinent variables through statistical analysis

In addition to this finding, individuals with higher levels of spatial ability also experienced less overall cognitive load than individuals with lower spatial ability, where individuals that experienced higher levels of cognitive load had poorer complex problem-solving performance. This indicates that these students may have been experiencing extraneous cognitive load which can hinder their capacity to solve the problem, learn from the experience, and influence their motivations to engage in similar activities in the future (Chen & Kalyuga, 2020; Paas et al., 2004; Sweller et al., 2019). However, through this research a possible means of addressing this issue has been identified. As spatial ability is a malleable cognitive factor, spatial skills may be developed to support lower visualisers in developing more holistic problem-solving approaches and managing cognitive resources during problem solving. Spatial skills can be developed through direct and indirect approaches e.g., spatialising curricula and semester-long training interventions (Julià & Antolí, 2017, 2016; Mohler & Miller, 2008; Sorby, 2005; Sorby & Baartmans, 1996). Where spatialising curricula includes the use of spatial activities, using symbolic systems, analogical learning, and learning which is grounded in embodied experience (Newcombe, 2017). Newcombe (2017) details specific approaches that educators and curriculum designers can integrate into practice for developing spatial skills to support STEM learning.

This research sought to contribute towards addressing the gap in understanding of the cause of spatial abilities relationship to success in STEM disciplines and contribution to individuals problem-solving approaches. The findings of this work indicate that spatial ability supports the management of cognitive resources during problem solving and more successful problem-solving approaches. Although this study was a single site study and therefore the findings are not widely generalisable, the findings do indicate that it is necessary to further explore the relationship between spatial ability and cognitive load experienced in STEM education to work towards understanding why spatial ability relates to STEM success. Future work may look to examine the relationship between spatial ability and cognitive load on various types of problems, in varying contexts and environments as a means of advancing this understanding.

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