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Using pupil dilation to measure cognitive load during a spatial skills test

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Abstract

This paper explores how spatial skills and cognitive load interact for engineering students. Spatial skills allow a person to manipulate and rotate a three-dimensional object in their “mind’s eye.” Studies have reported that spatial skills can be a reliable predictor of problem-solving success in engineers. Despite the comprehensive literature on spatial skills, the cognitive load experienced while solving spatial items among engineering students is not fully understood. Using an eye tracking device, this study explored how the cognitive load experienced by high spatial visualizers differs when compared to low spatial visualizers in solving spatial tasks. Pupil dilation was recorded as a measure of cognitive load via an eye-tracking device as studies have shown that cognitive load causes a task-evoked pupillary response. Previous studies have shown that there is a linear increase in pupil dilation as cognitive load increases.

The current study was conducted in two phases. The first phase recruited 143 undergraduate engineering students from two large, public, R1 institutions. Participants completed three spatial tests in phase 1. Based on their performance on the spatial tests, 35 participants were purposefully selected for the second phase of testing. While the first phase was conducted over a web conference platform, participants came in person for the second phase so that they could wear an eye-tracking device while completing further tasks. The phase 2 tasks included tests in spatial and verbal analogy and solving six engineering mechanics problems with increasing levels of difficulty. Data related to gender, race, and ethnicity were collected to understand if there were differences by demographic group. The larger study aims to examine several factors, including cognitive load, for high and low spatial visualizers while solving the six mechanics problems. In this paper, analysis results from the spatial testing component of the phase 2 testing will be presented.

Background

According to Thurstone’s theory of Primary Mental Abilities, spatial ability is defined as an outcome in the cognitive theory of intelligence [1, 2]. According to this theory, spatial thinking is a key cognitive construct that comprises different unique skills including, recalling, transforming mental images, translating maps, navigating, and interpreting graphs and diagrams [3]. Numerous research studies have indicated that spatial ability can predict success in STEM [4-11]. There has been a great deal of research using mental rotation tasks that has focused on the relationship between the complicated cognitive processes involved in mental representation and spatial thinking ability [12-14]. Such mental rotation research identifies individual differences in cognitive strategy selection. This is due to the fact that people adapt their cognitive strategy depending on their level of cognitive ability (such as spatial ability) when the item difficulty changes.

The most commonly applied theory regarding how a cognitive system creates a mental representation of any visual problem is that the representations emerge as a step-by-step process. In this case, the person segments a problem and then internalizes the segments to represent the whole problem, a process commonly referred to as a piece-meal strategy [12]. People who solve mental rotation problems using a piece-meal strategy typically divide the problem into several smaller pieces, mentally rotating one segment into congruence with the comparison figure and then rotating other segments to confirm parity. Just and Carpenter theorized that some participants use a piece-meal strategy to find the right choice when solving mental rotation problem; whereas, Norton and Stark found that an internal representation may be created by cognitively concentrating on the angles or any other physical features of the problem [15] [16]. This suggests that solving spatial problems will create cognitive load. Many researchers have attempted to learn more about the underlying cognitive processes in solving mental rotation problems, but none have yet led to a conclusive answer [17].

Eye fixation sequences during mental-rotation tasks can also give evidence of using a piece-meal strategy [18] [19] [15]. Just and Carpenter discuss in their research that a certain pattern of eye fixation shifts may suggest a piece-meal rotation strategy. Therefore mental rotation strategies may be assumed to process through eye movements, where retaining gaze on a specific location is related to our ability to visually encode spatially distributed information [18] [20] [21]. Thus, eye-tracking technology provides a great opportunity to investigate complex cognitive constructs that cannot be measured using other data collection methods. Eye-tracking has also been preferred over other physiological measurement systems because it offers the greatest potential for a reliable, non-invasive estimate of cognitive load. Over the past decade, researchers have focused on using pupil dilation as an index of effort in cognitive controlled tasks [22] [23] . Eye-trackers produce an ample amount of time series data allowing researchers to incorporate advanced statistical analysis to detect individual differences in pupil dilation. Pupil dilation can serve as a proxy for interpreting the cognitive load experienced while solving many types of tasks, including spatial thinking tasks. The pupil’s diameter is an indicator of cognitive load where the relationship between pupil dilation and task difficulty is linear i.e., pupil diameter increases with problem difficulty [23-26]. In this paper, we offer an estimate of the cognitive load experienced during a spatial test based on analysis of changes in pupil dilation.

Purpose and Hypothesis

The purpose of this study was to explore cognitive load while taking spatial visualization tests, comparing differences by varying levels of spatial skill. The cognitive load of participants was measured by pupil dilation. The hypothesis of this work is: There is a difference in cognitive load (as measured by pupil dilation) between low and high spatial ability students as they are solving spatial tasks.

Method

Setting and Participants

The current study took place at the University of Cincinnati and the University of Nebraska-Lincoln in their respective Colleges of Engineering. In the first phase of the study, 143 undergraduate engineering students completed three widely accepted tests of spatial cognition and provided researchers with demographic data. All phase one testing was accomplished online. In the second phase of the study, participants were invited to a classroom for taking a fourth spatial test as well as some additional tests that will not be reported on here. The room had standard ambient light. All mandatory COVID protocols were followed during the phase two testing. The participant was inside the room alone while taking the tests and observed by a researcher from outside through glass panes in the walls and the door. The sample for Phase 2 of the study included 10 Female and 19 Male students.

Data collection

The three spatial tests used in this study included the Mental Cutting Test (MCT) [4], the Paper Folding Test (PFT), and the Surface Development Test (SDT) [27]. A purposive sample of 35 participants, based on their level of spatial ability and gender, were invited to participate in the second phase. In the second phase, the selected participants wore an eye-tracking device as they completed a verbal analogy test, a fourth spatial reasoning test and solved six engineering mechanics problems with increasing levels of difficulty. The second session of the research study was administered in a neutral location outside of the students' typical schedule.

Spatial reasoning test

Spatial reasoning tests are tests are intended to determine a participant's ability to manipulate 3D objects, visualize movements and change between shapes, and spot patterns between those shapes. The fourth assessment used in this study consisted of 10 questions designed to see how well a person can visualize folding a pattern to make a three-dimensional object. The assessment was comprised of 2-D patterns that could be folded to form a cube. All of the faces of the cube had differing shading or designs on them. Figure 1 shows an example problem from the fourth spatial test administered to students in this study. In this test, a pattern is given, and students are instructed to select the one 3-D cube that *cannot* be formed by folding up the pattern.

Pupil Dilation

In the second session, Tobii Pro Glasses 3, the third generation of Tobii wearable eye-tracking glasses, was used to measure pupil dilation as an indicator of cognitive load. The head unit has 16 illuminators and 4 eye cameras integrated into lenses, allowing optimal positioning, and providing an unobstructed view for the wearer by using interchangeable nose pads in 3 sizes. The unit is also integrated with a Full HD resolution scene camera with a 106^{o} combined field of view. The recording unit collects the eye-tracking data and wirelessly saves it onto an SD card. This recording unit is a pocket-sized unit that allows the test participant to move freely around the room. The researchers used Tobii Pro Lab software for analysis because it provides powerful tools for analysis and the software is tailored to satisfy most research needs including aggregation, interpretation, and visualization of data.

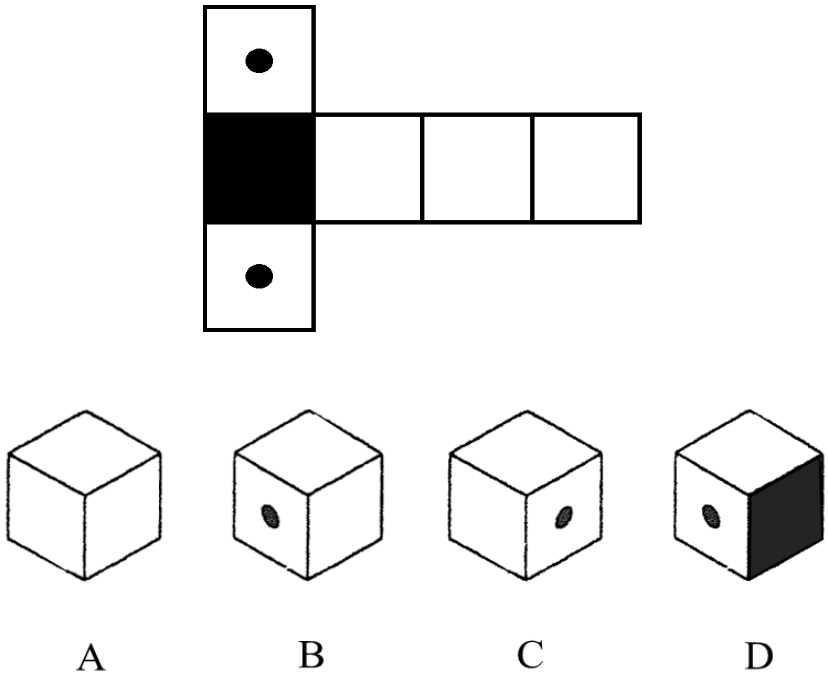

Figure 1: Spatial Test - Example Question (Correct Answer is A)

Data Analysis

Data collected by the eye-tracking system was used to determine pupil diameter for each participant. Timestamps were used to separate the measured pupil diameter for each of the 10 questions on the spatial reasoning test. Participants were separated into two groups, high and low spatial ability students, based on their spatial scores from the first phase of the study. These groupings will be used to explore the relationship between the cognitive load experienced while taking spatial tests for students of various spatial skill levels.

Results

Six participants were removed from the study due to incomplete data, leaving 29 participants (10 Female, and 19 Male) included in the final analysis. As noted previously, participating students were assigned to two different levels of spatial skill levels (high and low). Mean and Standard Deviation (S.D) were computed for the spatial scores. The score ranges on the combined spatial test (i.e., Mental Cutting Test, Paper Folding Task, and Surface Development Task) for each level were high (> Mean + S.D) and low (< Mean – S.D). The total possible score for the combined three tests administered in phase one was 103. There were 8 students in the low spatial visualizer group, and 6 students in high spatial visualizer group.

Firstly, a Pearson correlation analysis was conducted to understand if spatial scores from phase one and phase two were related to one another. The spatial scores for the phase 1 score and phase 2 tests were found to be strongly positively correlated, r (28) = 0.691, $p < 0.001$. A Pearson correlation analysis was also conducted to determine the relationship between the questions used in the fourth spatial reasoning test and it was found that all the questions were moderately positively correlated with one another with statistical significance $p < 0.05$. This correlation analysis was conducted as test of reliability with other spatial tests.

Pupil dilation was calculated for each question by subtracting the baseline diameter from the task-specific diameter. Task-specific diameter relates to the diameter of the pupil when the participant is solving the problem. An Independent sample t-test was conducted to understand whether the differences between pupil dilation for high and low spatial visualizers was statistically significant for each of the 10 questions on the spatial reasoning task (denoted by Q1-Q10). Results are tabulated in Table 1. We used only correct responses for this test. We used Hedge's to find the effect size because of small sample size. For Q8, Glass' delta was calculated because the standard deviations are significantly different.

Table 1: Independent Sample Test- Spatial Skill Levels and Pupil Dilation for Spatial Reasoning Test

	Level of Difficulty	High (Average)	Low (Average)	t	p-value	Mean Difference	Std. Error Difference	Effect size	
								Hedge's g	Glass's delta
Q1	0.966	0.282	0.122	-2.238	0.045	-0.161	0.072	1.209	
n=		6	8						
Q2	1	0.126	0.243	1.287	0.222	0.117	0.091	0.695	
n=		6	8						
Q3	0.724	0.093	0.117	0.239	0.818	0.024	0.100	0.169	
n=		6	3						
Q4	0.897	0.136	0.224	0.706	0.496	0.088	0.125	0.407	
n=		6	6						
Q5	0.966	0.14	0.168	0.299	0.771	0.028	0.095	0.166	
n=		6	7						
Q6	0.793	0.164	0.216	0.660	0.526	0.052	0.078	0.274	
n=		6	5						
Q7	0.69	0.216	0.084	-1.154	0.287	-0.132	0.114	0.815711	
n=		6	3						
Q8	0.931	0.199	0.221	0.199	0.848	0.022	0.111	0.114651	0.172
n=		6	6						
Q9	0.759	0.344	0.181	-1.239	0.255	-0.163	0.132	0.831149	
n=		4	5						
Q10	0.517	0.300	0.298	-0.016	0.988	-0.003	0.168	0.011228	
n=		6	3						

From this analysis, it was found that Q1 had a statistically significant effect on the pupil dilation for the high and low spatial visualizers, t(-2.238)=9.104, p=0.045. All other analysis indicated that there was not a significant effect detected on the pupil dilation values at the $p < 0.05$ level between the spatial levels (high and low) for the 10 questions in the spatial reasoning test. An independent sample t-test was also conducted to understand if there was statistical significance between the groups and overall pupil dilation data. In this test, we did not remove any participants. Results of this analysis are presented in Table 2. No significant effect was found on the pupil dilation values at the $p < 0.05$ level for high and low spatial levels for overall pupil dilation data during the spatial reasoning test.

From the data presented in Table 1, some interesting observations can be made. Q7 is the second most difficult problem on the test; pupil dilations for the low visualizer group are the smallest. This could indicate that the students in this group didn't really attempt to solve the problem and merely guessed at the correct answer. In contrast, Q10, the most difficult of all the problems, showed relatively high pupil dilations for students in both groups. Since the data presented in Table 1 is only showing results for those who answered the problem correctly, it could be that many of the people who might not have attempted to solve the problem guessed incorrectly and got it wrong. Further, for most questions (2, 4, 5, 6, 8, and 10), the low visualizers had larger pupil dilations than did their high visualizing peers. For the three questions where student pupil responses did not follow this pattern (for Q10, responses between the two groups are essentially equal), Q7 appears to have required no mental effort for low visualizers (likely guessing as described earlier), Q1 which was the first problem on the test and might have been anxiety-producing for the high visualizers for some reason, and Q9 which was one of the more difficult problems on the test with many low visualizers guessing at the correct answer after an initial input of effort. Further analysis of the data in terms of tracking eye movement is required.

Table 2: Independent sample t test- Spatial Skill Levels and Pupil Dilation for Spatial Tests

	High (Average)	Low (Average)	F-value	*p* -value	Hedge's g effect size
Overall	.195	.169	.128	.733	.192

Discussion and Limitation

Over the past decades, researchers have demonstrated the importance of spatial visualization for success in engineering, but there has been limited literature focused on exploring the cognitive load experienced by students while taking spatial tests. It is known from the literature that an increase in pupil dilation is an indicator of cognitive load. Therefore, this study sought to explore whether solving spatial test items increases cognitive load in participants through analysis of pupil dilation. One of the major limitations for this study is what baseline pupil diameter were used for the analysis. In literature, baseline pupil diameter is determined at the beginning of any test session.

Since this session had three test and the spatial test was the second of them. We did not use the baseline pupil diameter instead we used the different pupil diameter (i.e when students were reading instructions for the spatial test) for analyzing that might have skewed the results.

Nearly all participants experienced increased cognitive load while taking the spatial tests. The measured change in pupil dilation was in the range of -0.0382 and 0.42085. The positive change in pupil diameter indicates an increase in cognitive load while taking the spatial test for many students. The extracted eye tracking data indicated that 65% of participants experienced cognitive load in the range of 0.10 – 0.50. In some cases, negative pupil dilation was detected, the cause of this can be interpreted in a couple of ways such as: a) while reading the instructions for the test, students would have spent time figuring out their approach mentally which increased the intrinsic load for them at that stage. Therefore, their pupil dilation would have increased during this period. Once an approach was identified they implemented it which required less cognitive demand or cognitive load when solving the test questions. This would lead to a decrease in their pupil dilation during this stage resulting in negative pupil dilation when solving the problem or b) students gave up trying after the first few problems resulting in lesser cognitive load than the baseline measure leading to negative pupil dilation. The data collected here showed that the levels of the spatial score had no significant effect on pupil dilation. This could be because of the difference in the number of participants between groups or due to the small sample size included in this study. During the analysis, time spent on each of the questions was not taken into consideration, which may or may not have influenced the change in pupil diameter. Although in the literature there have been different metrics that have been used to study cognitive load, using pupil dilation alone in this analysis would have limited interpretation and understanding of the data.

The study was originally intended to take place during a normal semester, however COVID had a great impact on the second phase of the study. It brought about a lot of concerns for the selected students participating during the study and there were a lot of scheduling conflicts for this phase. Most of the participants were not around campus because most their classes were offered online, and they had to drive to campus to participate in the study. More data would have been a great addition for the interpretation of results to understand the cognitive load between levels of spatial skills.

Conclusion

Measuring pupil dilation using eye-tracking is seen as an effective way to evaluate cognitive load while solving spatial tests. Our results show that the students experience cognitive load while solving spatial skills. However, there was only statistical significance that was indicated between high and lower spatial visualizers for the Question 8. All other question did not have any statistical significance has been indicated between the levels (high and low) of spatial skill and cognitive load as measured by pupil dilation. This indicates that further analysis and research is necessary in this area.

Wearable technologies monitor an individual’s physiological response when engaging with a task, which previous research has demonstrated can be an indication of cognitive load [23] [24] [25] [26]. This data is collected in real-time and in an uninterrupted manner. In education settings, use of these technologies enables researchers to incorporate real time feedback to alleviate cognitive load, increasing flexibility and personalization of the learning and teaching process.

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References

[1] L. L. Thurstone, Primary mental abilities, Chicago: University of Chicago Press, 1938.

[2] J. Schneider and K. S. McGrew, "The Cattell-Horn-Carroll theory of cognitive abilities.," in *Contemporary Intellectual Assessment: Theories, Tests, and Issues.*, New York, The Guilford Press, 2018, pp. 73-163.

[3] A. Nazareth, R. Odean and S. Pruden, "The Use of Eye-Tracking in Spatial Thinking Research," in *Eye-Tracking Technology Applications in Educational Research*, Pennsylvania, IGI Global, 2016, pp. 239-260.

[4] S. A. Sorby, "Educational Research in Developing 3-D Spatial Skills for Engineering Students," *International Journal of Science Education,* vol. 31, no. 3, pp. 459-480, 2009.

[5] M. B. Casey, R. L. Nuttall and E. Pezaris, "Mediators of gender differences in mathematics college entrance test scores: A comparison of spatial skills with internalized beliefs and anxieties.," *Developmental Psychology,* vol. 33, no. 4, pp. 669-680, 1997.

[6] D. Lubinski, "Spatial ability and STEM: A sleeping giant for talent identification and development," *Personality and Individual Differences,* vol. 49, no. 4, pp. 344-351, 2010.

[7] M. Kozhevnikov, M. A. Motes and M. Hegarty, "Spatial Visualization in Physics Problem Solving," *Cognitive Science,* vol. 31, no. 4, pp. 549-579, 2010.

[8] K. Atit, J. R. Power, N. Veurink, D. H. Uttal, S. Sorby, G. Panther, C. Msall, L. Fiorella and M. Carr, "Spatial Skills as Predictors of Success in First-year Engineering," in *2014 IEEE Frontiers in Education Conference (FIE) Proceedings,* Madrid, Spain , 2014.

[9] J. Wai, D. Lubinski and C. P. Benbow, " Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance," *Journal of Educational Psychology,* vol. 101, no. 4, pp. 817-835, 2009.

[10] S. Sorby, E. Nevin, E. Mageean, S. Sheridan and A. Behan, "Initial investigation into spatial skills as predictors of success in first-year STEM programmes.," in *SEFI 2014 42nd Annual Conference European Society for Engineering Education*, Birmingham, UK, 2014.

[11] S. Sorby, N. Veurin and S. Streiner, "Does spatial skills instruction improve STEM outcomes? The answer is ‘yes’," *Learning and Individual Differences,* vol. 67, pp. 209-222, 2018.

[12] J. Xue, C. Li, C. Quan, Y. Lu, J. Yue and C. Zhang, "Uncovering the cognitive processes underlying mental rotation: an eye-movement study," *Scientific Reports,* vol. 7, no. 10076, pp. 1-12, 2017.

[13] Z. W. Pylyshyn, Seeing and Visualizing It's Not What You Think, Cambridge, MA: MIT Press, 2003.

[14] R. N. Shepard and J. Metzler, "Mental rotation of three-dimensional objects," *Science,* vol. 171, no. 3972, pp. 701-703, 1971.

[15] M. A. Just and P. A. Carpenter, "Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability," *Psychological Review,* vol. 92, no. 2, pp. 137-172, 1985.

[16] D. Noton and L. Stark, "Eye movements and visual perception," *Scientific American,* vol. 224, no. 6, pp. 34-43, 1971.

[17] S. Johnston, E. C. Leek, C. Atherton, N. Thacker and A. Jackson, "Functional contribution of medial premotor cortex to visuo-spatial transformation in humans," *Neuroscience letters,* vol. 355, no. 3, pp. 209-12, 2004.

[18] M. A. Just and P. A. Carpenter, "Eye fixations and cognitive processes," *Cognitive Psychology,* vol. 8, no. 4, pp. 441-480, 1976.

[19] S. Walcher, C. Körner and M. Benedek, "Looking for ideas: Eye behavior during goal-directed internally focused cognition," *Consciousness and cognition,* vol. 53, pp. 165-175, 2017.

[20] R. H. S. Carpenter, "Movements of the eyes," in *Chapter 4*, London, Pion Ltd, 1988, pp. 93-94.

[21] R. N. Shepard and L. A. Cooper, "Chapter 2," in *Mental Images And Their Transformations*, MA, The MIT Press, 1986, pp. 236-239.

[22] B. Cowley, M. Filetti, K. Lukander, J. Torniainen, A. Henelius, L. Ahonen, O. Barral, I. Kosunen, T. Valtonen, M. Huotilainen, N. Ravaja and G. Jacucci, "The Psychophysiology Primer: A Guide to Methods and a Broad Review with a Focus on Human–Computer

Interaction," *Foundations and Trends® in Human–Computer Interaction,* vol. 9, no. 3-4, pp. 151-308, 2016.

[23] P. V. d. Wel and H. v. Steenbergen, "Pupil dilation as an index of effort in cognitive control tasks: A review," *Psychonomic Bulletin & Review,* vol. 25, pp. 2005-2015, 2018.

[24] E. H. Hess and J. M. Polt, "Pupil Size in Relation to Mental Activity during Simple Problem-Solving," *Science,* vol. 143, no. 3611, pp. 1190-1192, 1964.

[25] D. Kahneman and J. Beatty, "Pupil Diameter and Load on Memory," *Science,* vol. 154, no. 3756, pp. 1583-1585, 1966.

[26] J. Beatty, "Task-Evoked Pupillary Responses, Processing Load, and the Structure of Processing Resources," *Psychological Bulletin,* vol. 91, no. 2, pp. 276-292, 1982.

[27] R. B. Kstrom, J. W. French, H. H. Harman and D. Dermen, Manual for kit of factor-referenced cognitive tests, Educational testing service, 1976.

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