

INVESTIGATING THE RELATIONSHIP BETWEEN SPATIAL SKILLS AND ENGINEERING DESIGN

G. Raju¹, S. Sorby¹, C. Reid²

¹*University of Cincinnati (UNITED STATES)*

²*Technological University of the Shannon: Midlands Midwest (IRELAND)*

Abstract

Design is a core attribute of engineering practice; in fact, the etymology of the word engineer is traced to the Latin “ingeniare,” which translates as inventor or designer. In order to prepare our students for success in an engineering career, they must be proficient at design and able to think creatively and flexibly about optimal solutions to problems. Additionally, numerous studies have demonstrated the need for well-developed spatial skills for success in engineering, especially in engineering problem solving. Studies also show a link between spatial thinking and technical creativity. The focus of this research is on understanding the relationship between spatial visualization skills and engineering design. As a first phase of testing, 127 undergraduate engineering students completed four tests of spatial ability. In a second phase, 102 students returned and were asked to complete three tasks. The first was designing a ping pong ball launcher to hit a target at a specific height from a given distance. They were then asked to list as many factors as possible that should be considered when designing a retaining wall for mitigating flood damage along the Mississippi River in the Midwest in the United States. The third task was to sketch as many ideas as possible in a given timeframe for a rainwater collection system in a remote location. This research paper will present preliminary analysis of the Midwest Flood problem and spatial ability data. The initial insights will be discussed relative to the overall study and how this work could inform undergraduate engineering education, and specifically the provision of design education.

Keywords: Spatial Ability, Visualization, Design, Engineering

1 INTRODUCTION

Design is often referred to as the process of imagining and planning the construction of an object or system for the implementation of a particular prototype. Design is considered an important characteristic and a central activity to many professions such as engineering, industrial design and architecture. These professionals use some kind of designs to solve different problems or devise new products in order to complete their job functions. In the past few decades, the position of design in engineering education has been recognized in the US in terms of national standards of engineering programmes. The Accreditation Board for Engineering and Technology (ABET) has included design as one of the seven outcomes that a student should attain prior to graduation [1]. Specifically, students must attain:

an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors [pp. 14].

Engineers graduating from ABET-accredited programs are expected to produce novel and unexpected solutions; work with incomplete information; apply imagination and use drawings as means of conveying ideas. Many studies have reported that design is a high-level cognitive skill [2-5]. The process of designing is defined as a cognitive activity that involves the production of successive iterative representations of an artifact, both internal and external, to analyse and improve the design [6-7]. There has been limited research focusing on the cognitive basis of the design thinking process [8-10]. Therefore, further investigation is required to confirm the consideration of design as a form of cognitive activity and to develop understanding of the cognitive processes of designerly thinking. It is crucial for engineering educators to understand not only the design process but also how the design problem-solving approaches of students differ and the underlying reason behind such variation.

1.1 Spatial ability and Design Thinking

Spatial ability is considered to be one of the key cognitive elements necessary for a designer and plays an important role in well-established theories and models of intelligence [11-12]. It is strongly associated with prediction of success in STEM [13-19] as spatial ability helps individuals improve their capacity to visualize images and mentally manipulate and transform them in different ways [20-22]. Many researchers have studied the importance of spatial thinking in courses such as graphics and the implication of poor spatial skills on success rates and career choice [23-25]. However, to date there has been limited research about the effect of spatial ability on design thinking [25-26]. In this paper, the aim is to begin to explore the relationship between spatial visualization skill levels and engineering design in order to advance research in this area.

2 METHODOLOGY

The study was conducted through a correlational research design [27]. Correlational research designs are used to describe and measure an association or relationship between two or more variables or scores. This design was used to answer the following research question: "How does spatial visualization relate to students' performance on an open-ended engineering problem?".

2.1 Setting and participants

The current study took place at a large public university with very high research activity and was conducted through the College of Engineering and Applied Science. In the first phase of the study, participants completed four widely accepted tests of spatial ability and provided researchers with demographic data. All phase one testing was completed online. In the second phase of the study, returning participants completed three design tasks in person. All mandatory COVID protocols were followed during the phase two testing.

2.2 Data collection

The first phase of the study involved 127 undergraduate engineering students who completed four spatial tests online. The four spatial tests included: the Mental Rotation Test (MRT), the Mental Cutting Test (MCT), the Paper Folding Test (PFT), and a Spatial Orientation Test. When measuring a cognitive factor such as spatial ability, multiple tests are commonly administered to obtain a precise measure of the factor [28]. A Verbal Analogy Test was also administered as a control for general intelligence. After the first session, all participants were invited to attend the second session. 103 participants returned for the second phase of the study. In this phase, the participants completed three short open-ended design problems which included: design of a Ping Pong launcher, the Midwest Flood listing problem, and a Remote Village Rainwater Catcher design task. The second session of the research study was administered in a neutral location outside of the students' typical schedule, allowing for every student to take the test in a neutral setting.

This paper will focus on the results from the Midwest Flood listing task only. In the Midwest Flood task, participants were asked to list the factors that should be considered in designing a retaining wall for the Mississippi river to mitigate floods in the Midwest. Participants were allowed to use the internet to search for any information that would help them list the factors and were asked to cite the source in the answer sheet and not to plagiarize any published work. The researcher circulated through the room to ensure that students were working independently on the task.

2.3 Data analysis

In phase one, the four spatial tests were graded and, due to the fact that each test had a different number of points possible, those scores were converted to an overall Z-score for each student. Z-scores were used in the analysis throughout this paper. In phase two, the students' written responses from the Midwest Flood design task were coded into segments based on the coding scheme developed and validated by Atman et al [29] [30]. The coding scheme consists of two broad knowledge dimensions containing four categories in each of dimension. The first dimension, "physical location", refers to the physical area of focus for the construction of the wall, including the wall itself, water, bank, and surroundings. The second dimension, "frame of reference" includes the categories such as technical, logistical, natural, and social factors to consider in the construction. Descriptions of each of the two dimensions are shown in the Table 1. Since this problem was a listing task, it was more like a task measuring a student's ability to engage in "divergent thinking."

Table 1. Code descriptions

<i>Physical Location</i>	<i>Description</i>
Wall	The wall itself, things that interact with the wall, alternatives for wall, where to build the wall
Water	Length of the river, fish, flood (but not effects of flood on other locations), pressure issues (without mention of the wall)
Bank	Land immediately adjacent to river, earth below the river (Riverbed), interface of the wall, edge of the river, width of the river
Surroundings	Anything away from the water, living areas, things along the water, specific effects of the wall or flood to the shore
<i>Frame of Reference</i>	<i>Description</i>
Technical	Technical or engineering vocabulary, design issues, decisions about the wall or about having the wall
Logistical	Cost, funding, construction process, maintainability issues, resources needed
Natural	Volume of water, damage, effects of flood, topography, animals, plants, weather and weather predictions
Social	People, safety concerning people, towns, living areas

The student responses were independently coded by two researchers and codes were discussed between them to reach consensus. Inter-rater reliability was calculated, and the value of Kappa was found to be 0.967 indicating a significant level of agreement between the two coders. These qualitative codes were then transformed into numeric form based on the number of codes listed by students under each frame of reference for statistical analysis. So, the total codes points would be the total number of factors listed by students from both knowledge dimensions.

3 RESULTS

Out of 102 participants, 1 participant was removed due to incomplete answers. Table 2 shows the correlation between the independent spatial test scores, total spatial Z-scores, and total coded points. The independent spatial test scores (MRA, MCT, PFT, SOT) were found to be very weakly positively correlated with one another in the range of 0.296 - .373. Correlations between the individual spatial tests were statistically significant with p-values <0.001 for each correlation. From the correlation matrix, it is clear that there is some level of relationship between the spatial scores for the individual tests. However, the total code points did not correlate significantly with total or independent spatial scores. To further investigate the research question, the participants were grouped into two groups; high and low spatial visualizers based on the average score (mean) of all the participants. Standard deviation (SD) was also calculated. High spatial visualizers were those who scored more than one standard deviation above the mean ($>\text{Mean} + \text{SD}$) and low spatial visualizers were those who scored less than one standard deviation below the mean ($<\text{Mean} - \text{SD}$).

An independent sample t-test was also performed to investigate whether the differences in divergent thinking of high and low spatial visualizers were statistically significant. Results are tabulated in Table 3. From this analysis, there was not a significant effect on the total code points at the $p < 0.05$ level for the two spatial levels (high and low) [$t_{27.578} = 1.138$, $p = 0.120$]. It was observed that the average number of code points for the lower spatial visualizers was higher than average of the high spatial visualizer. This could be a result of an uneven number of participants in each group. Also, it was observed that lower visualizers spent 1.19 minutes on average more time on the task than high spatial

visualizers. There was no statistical significance effect on time spent at the $p < 0.05$ level for the high and low spatial visualizers [$t_{20.882} = 0.717$, $p = 0.761$].

Table 2: Correlation matrix for spatial scores and coded points

	<i>Total Code Points</i>	<i>MRA</i>	<i>MCT</i>	<i>PFT</i>	<i>SOT</i>
<i>Total Code Points</i>					
<i>MRA</i>	.062				
<i>MCT</i>	.134	.296**			
<i>PFT</i>	-.034	.332**	.339**		
<i>SOT</i>	-.027	.373**	.495**	.327**	
<i>Total Spatial Score</i>	.014	.658**	.755**	.666**	.741**

Table 3: Independent Sample t Test

	<i>High</i>	<i>Low</i>	<i>F-value</i>	<i>p-value</i>	<i>Eta (η) effect size</i>
<i>Total Code points</i>	10.461	12.529	2.577	.120	-0.411
<i>Time Spent on the Task</i>	9.10	10.29	.095	.761	0.2950

4 CONCLUSIONS

There has been substantial research indicating the importance of spatial visualizations skills in STEM, but there have been limited studies that have explored the relationship between spatial visualization skills and engineering design. The preliminary findings from this study indicate that there was no significant relationship between performance on the Midwest Flood task and student spatial visualization skills. However, the data analysis remains at a preliminary stage. It may be that the lack of association between the Midwest Flood task and spatial visualization skills is a result of this task being a listing or divergent thinking exercise. It also could be the case that there is a difference in the type of factors high and low visualizers list in this task. Further analysis is planned. The other two open-ended tasks included in the larger research study are distinctly different in that they require a more holistic approach to developing a solution to the tasks and consideration of multiple factors and means of depicting solutions. Future analysis will explore the relationship between spatial visualization skills and performance across each of the three tasks. It is intended that through this work understanding may be gained into how spatial visualization skills relate to engineering design. This insight could inform the refinement of educational approaches to foster the development of a key engineering skill, design capability.

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