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Exploring the Role of Spatial Visualization in Design Process of Undergraduate Engineering Students

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Abstract:

This research paper details a study investigating spatial visualization skills relation to design problem-solving for undergraduate engineering students. Design is outlined as one of the seven attributes that engineering students must demonstrate prior to their graduation as set out through the ABET guidelines. It is important to understand the factors that contribute to design capability to achieve this learning goal. Design problems by their nature are cognitive tasks and as such require problem solvers to draw both on learned knowledge and pertinent cognitive abilities for their solution. In the context of engineering design problem solving, spatial visualization is one such cognitive ability that likely plays a role. Previous research has demonstrated a link between spatial visualization and design. This work aims to advance on that research by exploring how spatial visualization relates to the design process enacted by undergraduate engineering students.

There were two phases to data collection for this research. In the first phase, 127 undergraduate engineering students completed four spatial tests. In the second phase, 17 students returned to complete three design tasks. This paper will focus on one of these design tasks, the Ping Pong problem where individuals are asked to design a ping pong launcher to hit a target from a given distance at a specific height. A purposive sample of 9 first-year and 8 senior students were selected to engage in a think aloud protocol during the problem-solving task based on their spatial visualization skill levels (high vs. low). The think aloud protocol was used to assign pre-defined codes for design activity for each of the 17 participants.

Through analysis of these codes, results indicated that there is an association between the spatial skills of students and the design processes/actions that they employ. These insights will be discussed relative to their potential influence on engineering education, specifically in developing design capability.

Key words: Spatial skills, problem solving, creativity, design, mixed method

Introduction

In today's global market, the workforce trained in Science, Technology, Engineering, and Mathematics (STEM) experience lower rates of unemployment and higher salaries, a phenomenon seen across all nations. Recent technological advancements in the engineering field have created an environment for educators to reconsider the ways they should be educating future engineers. Educational reform efforts have been spurred by concerns about competitiveness and the insufficient number of graduating engineers to fill vacant positions in the job market. Several organizations have released reports that describe the need for systemic change in the engineering education curriculum with a focus on skills that help graduates develop their employability skills, such as process, design and analytical skills [1] [2] [3].

Engineering design is a significant component of engineering education and a competency that a student needs to acquire to be successful in engineering. The engineering design process typically involves the development of a prototype that is tested and modified to achieve the desired outcomes of the problem statement. Design is exploratory, rhetorical, emergent, opportunistic, and an important human endeavor [4]. Even though the products from any design process are different, it is central activity that STEM professionals such as those from engineering, industrial design, and architecture should be equipped with to complete their job roles. In the past years, ABET has defined the importance of design in engineering education in terms of the accreditation criteria of engineering and engineering technology programs [5]. Engineering design was included as one of the seven student outcomes that a student should attain prior to graduation to prepare graduates to enter their professional practice of engineering [5]. Outcome 2 states that student must have:

> 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. 8].

Department must have an understanding of how students learn engineering design to meet ABET standards. Several researchers have used different frameworks for understanding engineering design [6] [7] [8]. Pahl noted several strategies that yielded good solution in his empirical studies of engineering design [9]. His studies described that using these strategies such as goal analysis, solution analysis, and decision making helps students to yield a good design. Many researchers have attempted to characterize the steps in the design process and studies have indicated that engineers typically iterate through several cycles of definition, testing and modification in their design solutions [10]. Therefore, it is crucial for engineering educators to understand not only the design process itself but also how design problem-solving approaches vary and the reason behind such variations among students.

Spatial Ability and Design Process

Spatial ability is considered essential for the scientific thought process and plays an important role in solving problems in engineering, science, and mathematics [11]. There is a strong association between the prediction of success in STEM and spatial ability as it improves an individual's ability to visualize images and mentally manipulate and transform them in different ways [12]. Several researchers are currently exploring the importance of spatial thinking in courses such as graphics, programming skills, and engineering mechanics [13] [14] [15]. However, there has been a dearth of literature that explores the impact of spatial ability on the engineering design process [16] [17]. The aim of this research study is to begin to address this gap and explore the relationship between spatial skills and engineering students' engagement in the design processes.

Methodology

In this research study, we use explanatory sequential design in the mixed methods research methodology, that utilizes two distinct strands i.e., the quantitative strand, in which numeric data are collected and analyzed followed by a qualitative strand, in which textual data are collected and analyzed consecutively [18]. The purpose of using this research design methodology is to use quantitative data to purposively, rather than randomly, sample for the qualitative phase of the study allowing us to interpret the quantitative data using the qualitative contextual data [19]. In further analysis, the data will be integrated to provide relevant information to explain the specific findings relative to the research questions [18].

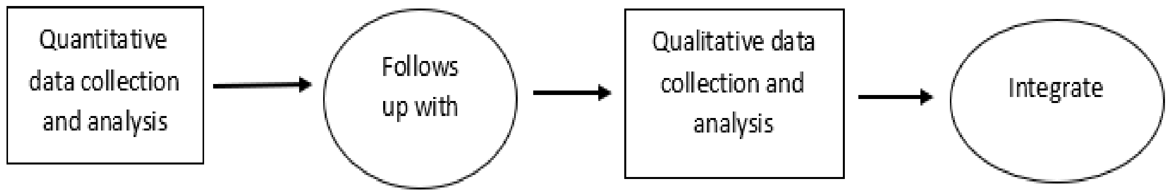


Figure 1: Explanatory Sequential Design

The purpose of this research study is to explore the association between spatial skills and engineering design process. The following research question guides this work: "What are the differences in design process for high spatial visualizers as opposed to low spatial visualizers when compared to level of expertise (i.e., first-years versus seniors)?".

Setting and participants

The current research study took place at a large public R1 university in the College of Engineering and Applied Science. The participants were engineering students who were in the first and final year of their respective engineering programs. They were recruited through recruitment flyers that were shared throughout the college. During the first phase of this research study, the participants completed four online widely accepted tests of spatial ability. In the second phase of the study, returning participants completed three design tasks with a concurrent verbal protocol in person. This study was conducted under the auspices of the university's IRB.

Quantitative Data Collection

In the quantitative phase of the study, 127 undergraduate engineering students completed four widely accepted tests of spatial ability online while being proctored by the research assistant. The four spatial tests included: The Mental Cutting Test (MCT), The Mental Rotation Test (MRT), The Paper Folding Test (PFT), and a Spatial Orientation Test (SOT). We also included a verbal analogy test as a control for general intelligence. The tests were scored, and participants were grouped into high, medium, and low spatial visualizers.

Qualitative Data Collection

Seventeen participants with either high or low spatial ability were purposively sampled to engage in a concurrent verbal protocol [20]. During this phase, participants were asked to individually complete three open-ended design problems; however, this paper will focus on the solution of only one of the three problems—the design of a ping pong ball launcher. The complete problem statement for this design task is below.

PROBLEM ONE: Ping Pong Problem

In an attempt to avoid boredom at your Hall, creative engineering students developed a challenging new game. A ping-pong ball is to be launched at a bullseye target, and points are awarded according to the accuracy of the landing. However, the ping-pong ball cannot be thrown at the target. It is up to you to design a device which will lift the ping-pong ball into the air and land it at the target. An accurate landing is desired while also maintaining a long flight time. Given that the center of the landing area is 5 meters away from the launch site, and the entire launching assembly must not be greater than 1m x 1m x 1m in dimension, design a ping-pong ball launcher for this game.

Your work should contain a detailed description of your design and should include any relevant diagrams and calculations. Please clearly state all assumptions which are needed in your analysis and try to keep your design simple yet effective.

Figure 2: Snapshot of the Ping Pong problem

This qualitative phase was administered in a neutral room inside the college without any external disturbances, allowing them to take the test in a restful setting. All the sessions were video recorded with the consent of the participants.

As each student completed the ping pong ball launcher design task, s/he was video recorded via zoom. The recording of each participant was then analyzed using the following sequence:

a) transcription – verbal protocol was transcribed from the video recording.
b) segmentation – dividing the verbal textual data into units that could be coded using a pre-defined coding scheme [21];
c) coding – using the previously established coding scheme, a design step was chosen to describe each student's "location" in the overall design process [22].

Two coders coded each segment of the design process for the individual participants. The coders checked their coding for interrater reliability, with an agreement level of 95% of the codes they had assigned. They then discussed their differences until they reached full agreement for each participant. The interrater reliability was calculated, and the value of Cohen's Kappa was found to be 0.965 indicating a high level of agreement between the two coders. This coded contextual data will help us to describe the design process/behavior employed by each of the participants. In addition, we were able to extract the percentage of time that each participant spent in various steps of the design process from the analysis of the video files.

TABLE 1

CODING SCHEME FOR THINK ALOUD DATA [21]

Design Activity	
(PD) PROBLEM DEFINITION	Define what the problem is, identify the constraints, criteria, reread problem statement or information from the question, question the problem statement
(GATH) GATHER INFORMATION	Search for and collect information
(GEN) GENERATE IDEAS	Develop possible solutions, brainstorm, list different alternatives, etc.
(MOD) MODELLING	Describe how to build the model, measurements, dimensions, calculations
(FEAS) FEASIBILITY ANALYSIS	Determine the workability of the design, meeting constraints, criteria, etc.
(EVAL) EVALUATION	Compare alternatives, judge options on which is better, cheaper, or accurate
(DEC) DECISION	Select one idea or solution from alternatives
(COM) COMMUNICATION	Communicate the design to others, write down a solution or instructions
(OTH) OTHER	None of the above codes apply or any other codes

Results

Quantitative Phase

Table 2 provides the descriptive statistics of the spatial scores from the phase 1 testing. There were only 21 seniors (10 Female and 11 Male) who participated in this phase, whereas 106 first-year students (32 Female and 74 Male) participated in the study. We grouped the participants into low, medium, and high spatial visualizers, but did not invite students from the medium group for further participation. Low spatial visualizers were students who scored less than 43, and higher spatial visualizers were students who scored more than 57. In the first-year group, the highest and low spatial scores were 86 and 12 respectively. In the senior group, the highest and low spatial scores were 70 and 26 respectively.

Qualitative Phase

From the purposive sampling, 8 seniors (3 Male and 5 Female) and 9 first-year students (3 Female and 6 Male) participated in the verbal protocol phase. Following the segmenting of the transcript into the design steps, we focused on exploring the overall amount of time spent on each of the design steps by high and low spatial visualizers. Table 3 summarizes the average time spent by each group for first-years and seniors. It was observed that students who were high spatial visualizers spent more time on the design process than low spatial visualizers.

TABLE 2

QUANTITATIVE DATA - SUMMARY

	Spatial Scores
Seniors (n = 21)	
Avg. Score	54.95
Std. Dev	11.55
First-year (n = 106)	
Avg. Score	48.63
Std. Dev	14.98

TABLE 3

SUMMARY STATISTICS FOR FIRST YEARS AND SENIORS: PING PONG PROBLEM

	Seniors (n = 8)	**First-years (n = 9)**
Time spent in design process	Avg. (min)	Avg. (min)
High spatial	26.9	22.75
Low spatial	19.5	10.92

After further investigation of the time spent on each design step, it was clear that high spatial visualizers spent a higher percentage of time on the feasibility step of the design process. This was observed for both first year and senior groups. Figure 3 clearly shows that seniors spend most of their time on feasibility, generating ideas, problem definition and modeling. These four steps in the design process sum to 83.75% of seniors' time and high spatial visualizers spent more than 50% of their time on the feasibility analysis of their design. Like seniors, Figure 4 reveals that first-years spend most of their time on feasibility, modeling, generating ideas and problem definition, for a total of 81.65% of their time in solving the problem. While seniors spent more time on feasibility than the other design steps, first-years spent proportionality equal percentages of time on problem definition, modeling, and feasibility averaging around 23.67%.

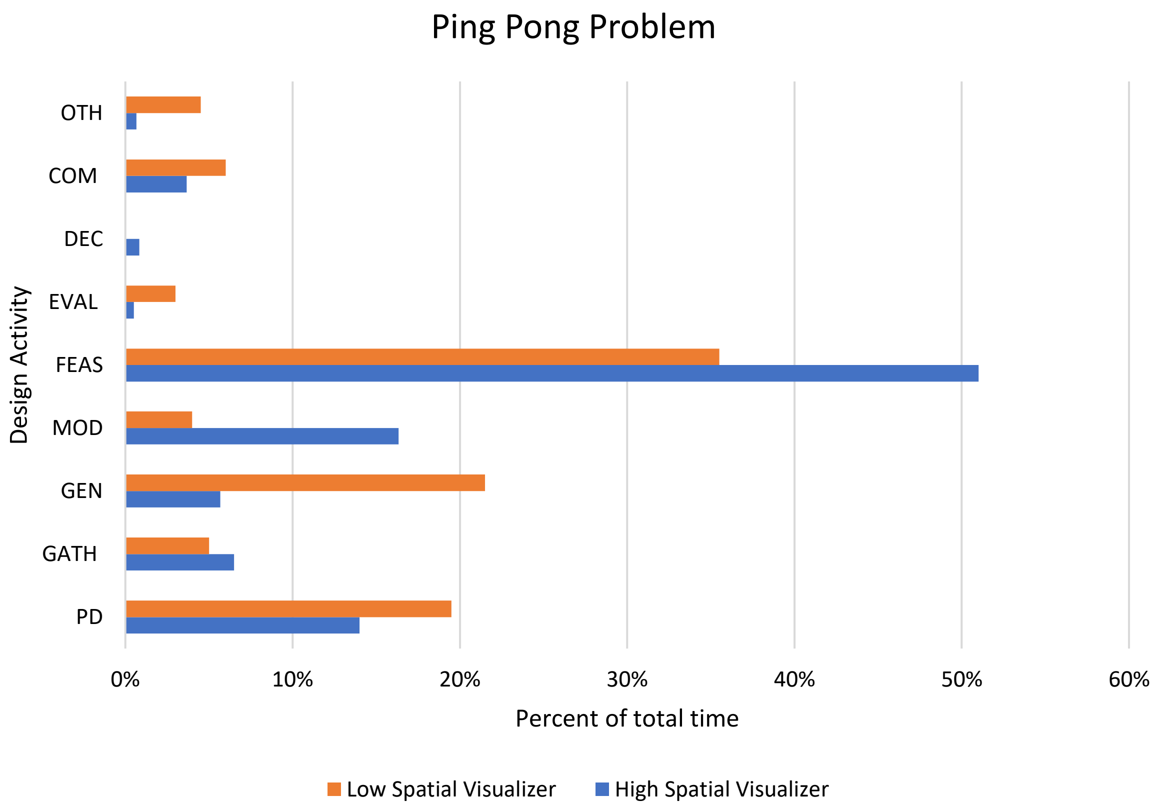


Figure 3: Average percent of time spent in each design step for senior.

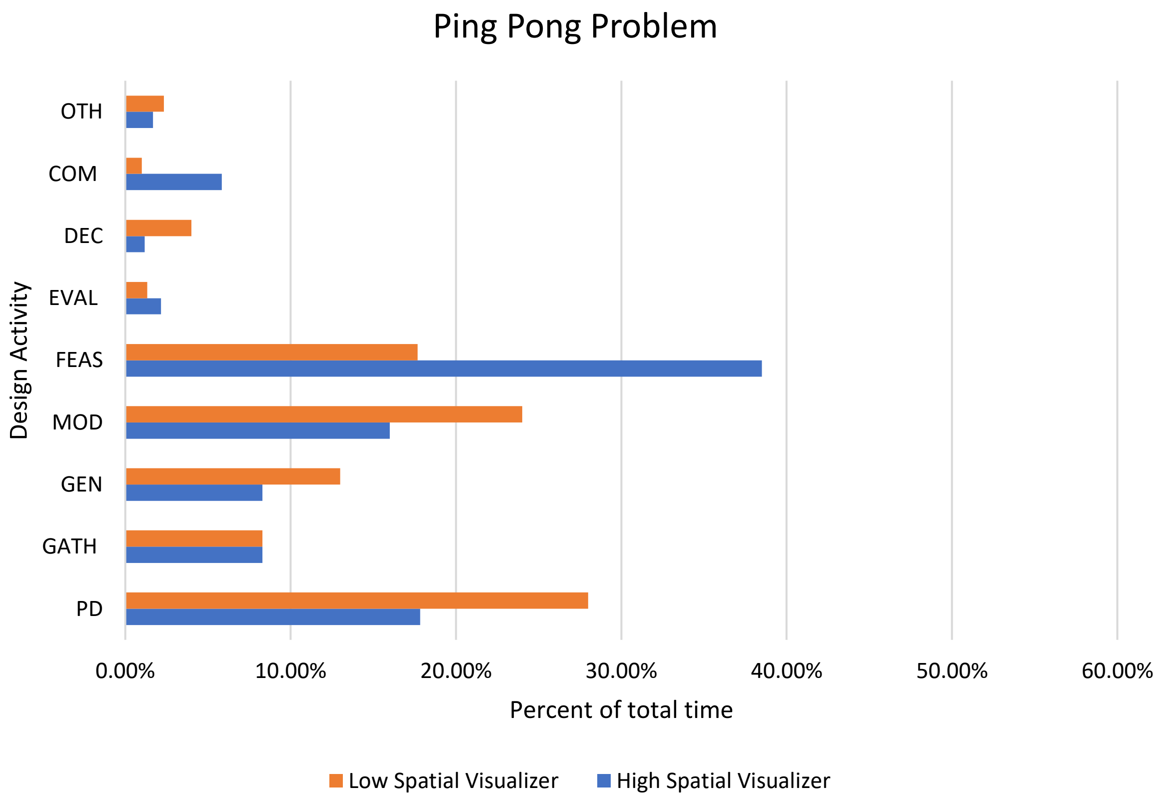


Figure 4: Average percent of time spent in each design step for first years.

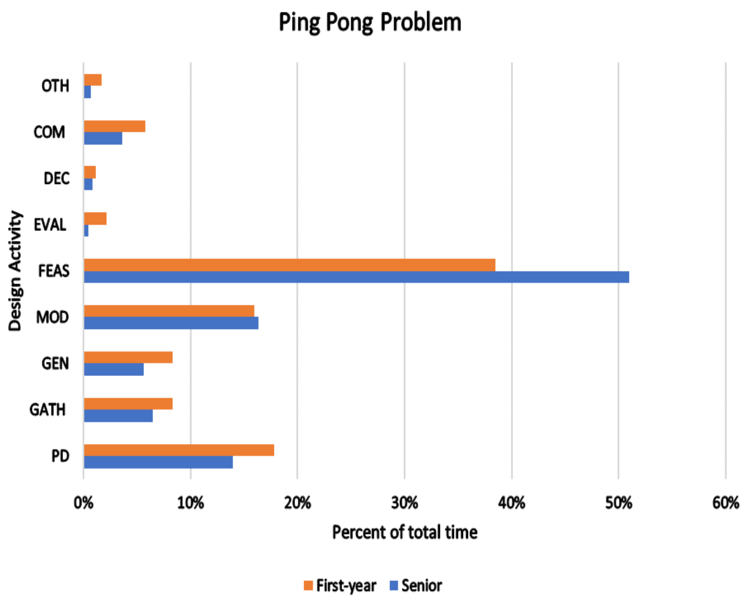
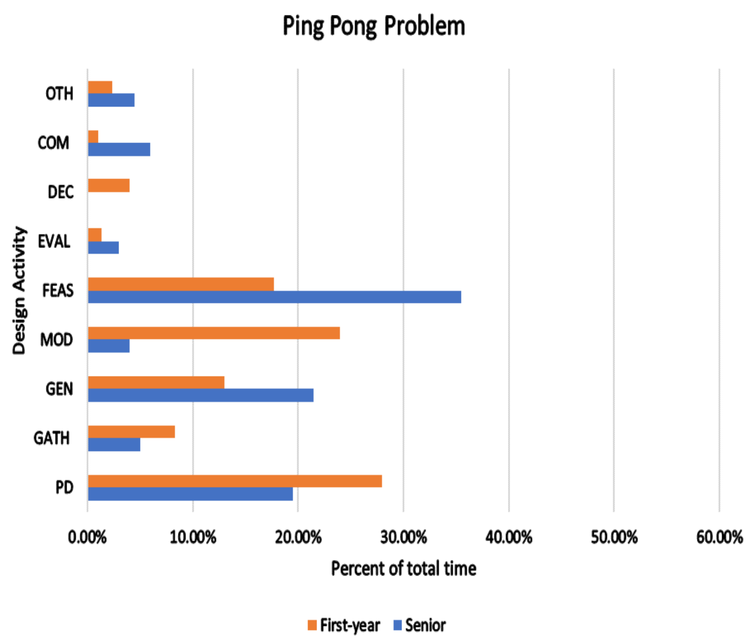
Level Spatial Skills	Avg. Scores	Average percent of total time spent
High		
Seniors (n=6)	62.17	
First-years (n=6)	69.5	
Low		
Seniors (n=2)	41.5	
First-years (n=3)	33.5	

Figure 5: Integrating the qualitative and quantitative data.

Integrating the results

Figure 5 shows the results delineated by spatial skill levels and expertise levels. In examining the high spatial group, it is apparent that seniors spend time on all design activities other than feasibility of the design. This could indicate that as expertise increases, participants focused more on the workability of the design idea during the design process, and less on the other aspects of design. Modeling and problem definition were the other top activities in the design process for these students.

For the low spatial visualizers, it is observed that the seniors still spent the majority of their time on the step feasibility of the design process, almost double the time spent by first-years. Also, from the examination of Figure 5, it is apparent that low spatial visualizers spent more time defining the problem and a larger percentage of time generating ideas when compared to the high spatial group.

In evaluating the segmented codes, it was observed that the design process steps of Generating Ideas (GEN), Modeling (MOD), and Feasibility Analysis (FEAS) were utilized more frequently than others in the design process. To further investigate the relationship between these design process steps and spatial scores, a Pearson correlation was conducted between total codes (GEN+MOD+FEAS) to understand their association with spatial score. There was a positive correlation between the two variables (i.e., total and spatial score), $r(15) = 0.334$, $p=0.189$, which should be cautiously interpreted given the small sample size in the study.

Discussion and Conclusion

Previous researchers have found that spatial skills have been a strong predictor of success in STEM but there has been a lack of research that has specifically explored the relationship between engineering design and spatial skills. For this research study, our main goal was to determine the differences, if any, in design process of high and low spatial visualizers based on the levels of their expertise. We observed from the results discussed in Figure 4, there are differences in the way high and low spatial visualizers solve a design problem based on their level of expertise (first-years versus seniors). High spatial visualizers spent more time in solving the design problem with focused attention towards feasibility analysis of design, almost as double percentage of total time when compared to low spatial visualizers. It is also observed that low spatial visualizers spent more time on problem definitions when compared to high spatial visualizers.

This research has qualitatively characterized the design process utilized by high and low spatial visualizers from a design cognition perspective and has shed some light on understanding the relationship between students' spatial skill levels and their process of solving a design task. These results may help to inform curricular changes that will benefit engineering students to move along a trajectory toward expert design behavior.

Acknowledgments

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