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Eye-Tracking Analysis of Problem-Solving Behavior in Design Tasks in Undergraduate Engineering: A Comparison of High and Low Spatial Visualizers

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Abstract

This research paper describes work performed at a large midwestern university in the U.S. examining the link between spatial skills and design performance. Spatial skills are vital to success in engineering education and their relation to efficient problem-solving is well-researched.

This study is part of a larger project focusing on understanding the link between spatial visualization skills and solving engineering design problems. In the current study, we made use of an eye-tracking device to determine the visual focus of participants while they solved an assigned design task. High and low spatial visualizers in undergraduate engineering were identified through Phase I testing. In Phase 1, students completed four widely accepted spatial ability tests. Subsequently, some students were invited to participate in a Phase 2 design problem-solving activity wearing the Tobii Pro Glasses 3 to collect eye tracking data to gain insight into the design problem-solving behaviors based on information collected about participants' eye movement fixations (i.e. duration and location). In this paper, we report on the analysis conducted through Tobii Pro Lab research software involving 13 study participants of whom 7 (1 female, 6 male: 3 first-year, 4 senior-year) were high spatial visualizers while 6 (3 female, 3 male; 4 first-year, 2 senior-year) were low spatial visualizers.

Findings from the study suggest that the solutions produced by the high visualizers were more graphical compared to low visualizers. Low visualizers focused more on the problem statement, spending more time reading it and coming back to it compared to high visualizers who remained in the problem solution area for most of the problem-solving session.

Recognizing the importance of spatial abilities in design problem-solving, educators can incorporate activities and exercises aimed at developing spatial skills among students which could include spatial reasoning tasks, visualization exercises, and hands-on design projects.

Keywords: Spatial skills, design thinking, eye tracking

1. BACKGROUND

1.1 Spatial Visualization

Spatial ability, identified as a cognitive process to construct, maintain, and manipulate 3-dimensional objects in one's mind [1, 2] has been linked with student success in STEM by many researchers as it is essential for comprehending complex concepts, such as geometry, engineering design, and physical processes [3-7]. Six separable spatial abilities i.e., spatial visualization, spatial orientation, spatial perception, spatial memory, spatial relations, and spatial reasoning have been identified to be the most important of spatial cognitive skills [9]. Visual-spatial ability, which is the subject of this research paper is “the ability to generate, retain, retrieve, and transform well-structured visual images” [9]. In STEM subjects, students with higher visual-spatial abilities can typically generate mental representations of intricate concepts and subsequently manipulate these representations. Such skills are crucial for fostering creative productivity and advancing theories within STEM domains [12].

Students possessing robust spatial visualization skills are more adept at interpreting diagrams, mentally manipulating three-dimensional objects, and tackling problems requiring spatial transformations [10]. Moreover, these skills transcend the boundaries of STEM disciplines, playing a pivotal role in professions like architecture, medicine, and design [11]. Thus, nurturing spatial visualization abilities in education becomes imperative as it not only cultivates proficiency across varied career trajectories but also furnishes learners with the cognitive prowess essential for problem-solving, innovation, and creativity in diverse contexts.

1.2 Design Thinking

In addition to spatial visualization, adequately performing engineering design tasks through an efficient design thinking process is another important skill for the success of engineering students. The engineering design thinking process is intricate, involving elements such as divergence-convergence, a systems perspective, ambiguity, and collaboration [13, 14]. The inclusion of engineering design as one of ABET’s seven student outcomes highlights its importance for graduation, ensuring that graduates are well-prepared to enter the professional practice of engineering [15]. Being effective at design thinking may lead to outcomes such as the capacity for innovative problem-solving [16], the capability to convert ideas to practical real-life solutions/applications [17], effective teamwork [18], leveraging uncertainties [19], developing a sense of responsibility and ethical decision-making [20]. All these characteristics are highly desirable in the engineering job market.

2. PURPOSE

As evidenced by the above discussion, spatial ability, and design thinking have independently been the subject of a significant number of research studies. Still, there is a scarcity of research that explores the relationship between spatial ability and design thinking. Only a handful of such studies exist where the implications [21] and influence [22] of spatial abilities on design thinking have been investigated. As a part of a larger project [23], this paper attempts to fill this gap by answering the following Research Question (RQ).

> ***RQ:*** *What are the various approaches to problem-solving in design tasks taken by engineering undergraduates with high or low visualization skills?*

To answer the above RQ, data was collected through wearable (glasses) eye-tracking technology while the study participants were solving a design problem.

3. EYE TRACKING METHOD FOR COLLECTING DATA

As a non-invasive assessment tool, eye tracking is a widely used data collection technique in research to analyze participant behavioral patterns while they perform tasks of interest to the researchers. In engineering design research, eye tracking has been used to assess the behaviors of professional engineers while they evaluate technical systems [24]. In engineering education, eye tracking has been used in manufacturing education [25], industrial design education [26], design education [27], and other fields.

Eye tracking was our preferred data collection method for this research due to several reasons. Eye tracking is one of the advanced tools that ensures the collection of precise and real-time data for research [28]. It directly measures attention, provides insights into cognitive processes, and offers researchers strong quantitative and qualitative data analysis capabilities [29].

In an eye tracking study, the aim is to make note of and assess the eye movements of the study participants. This is done by playing back and observing what the study participants are looking at and for how long they fixate on a specific point of attention. The path of transitions between any two points of attention is also recorded. The distinctive advantage of eye tracking resides in its capacity to furnish immediate, unbiased observations into human attention and cognitive functions. In contrast to conventional approaches like self-reports or behavioral observations, which can be influenced by biases or errors, eye tracking delivers accurate, real-time data on individuals' gaze behavior and attention distribution within a visual environment.

Primarily, an eye tracking device is expected to register eight types of readings [30]. They are 1) fixations, 2) fixation duration, 3) fixation count, 4) saccades or rapid eye movements between two fixations, 5) visit count or the number of visits to a specific fixation point, 6) visit duration, 7) scan path, and 8) pupil dilation. As can be seen in Figure 1, for our study, we collected our study participants' data through wearable eye-tracking glasses which recorded eye movements. We then used this data with the corresponding artifacts to prepare data for analysis through a desktop application. Further details of data collection and analysis are provided in the Methods section.

4. METHODS

4.1 Participants

This study was approved by the university IRB. Study participants were purposively selected from students who had previously completed several tests of spatial cognition, and comprised 13 engineering undergraduate students of whom 7 (1 female, 6 male: 3 first-year, 4 senior-year) were high spatial visualizers while 6 (3 female, 3 male; 4 first-year, 2 senior-year) were low spatial visualizers. They were selected to participate in the eye tracking study based on their responses to online spatial tests administered in the Fall of 2022 and their further consent to participate in the study. The online survey was shared with the study participants in the College of Engineering at the University of Cincinnati through their emails. Students who agreed to participate in the follow-up eye tracking study were assigned to complete 4 tasks (including the one that is the subject of this study). Each study participant received a 25 gift card for their participationnt in the eye-tracking studyonline spatial testing and an additional $100 for the eye-tracking study.

The spatial testing was used to identify them as either high or low spatial visualizers. A total of 325 undergraduate engineering students completed four widely accepted tests of spatial ability as a part of the testing. The four spatial tests included: the Mental Cutting Test (MCT) [31] the Mental Rotation Test (MRT) [32], the Paper Folding Test (PFT) [33], and the Spatial Orientation Test (SOT) [34]. The tests were scored, and participants were grouped into high, medium, and low spatial visualizers. A complete explanation of the scoring and categorization process is provided in our previous research [23]. Upon further communication, 22 of the respondents to the testing agreed to participate in the follow-up eye-tracking study. Data collected from 13 study participants were included in our analysis based on at least 85% Gaze Sample Quality [35].

4.2 The Design Task: The “Ping Pong Problem

Utilizing design thinking in a solutions-oriented, human-centered manner fosters creative problem-solving and innovation throughout the entirety of the engineering design process. The problem our study participants solved, required utilizing a design thinking process. The study participants were asked to solve the “Ping Pong Problem” [36]. As can be seen in the full problem statement (Appendix A), the problem consists of designing a ping pong launcher to throw a ping pong ball at a target situated at a distance of 5 meters. The launcher assembly is supposed to be 1m x 1m x 1m maximum in dimension. Participants were also asked to draw any relevant diagrams and include any calculations they might have performed in solving the task.

4.3 Eye Tracking Device and Data Collection

The eye tracking was done through wearable glasses, Tobii Pro Glasses 3 (Figure 1). Tobii Pro Glasses 3 feature 16 illuminators and 4 eye cameras seamlessly integrated into lenses, enabling

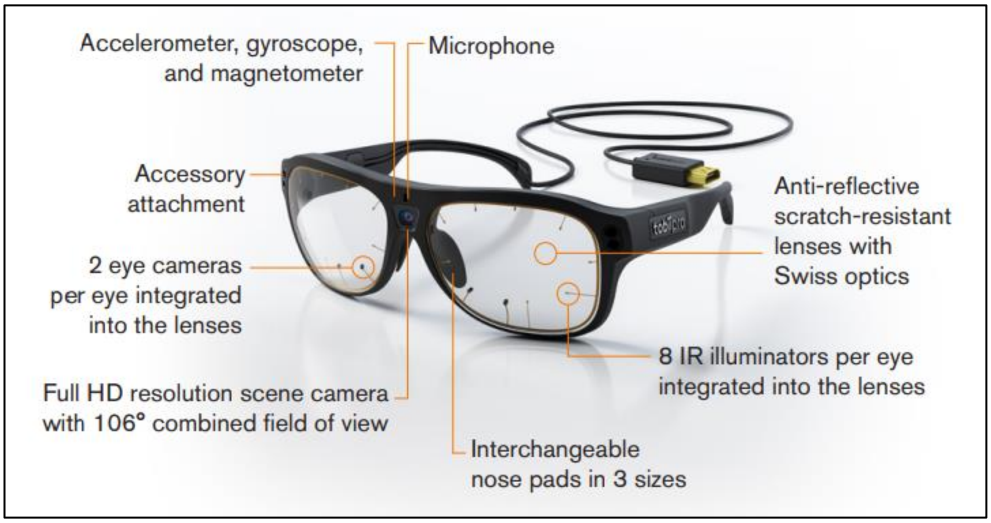
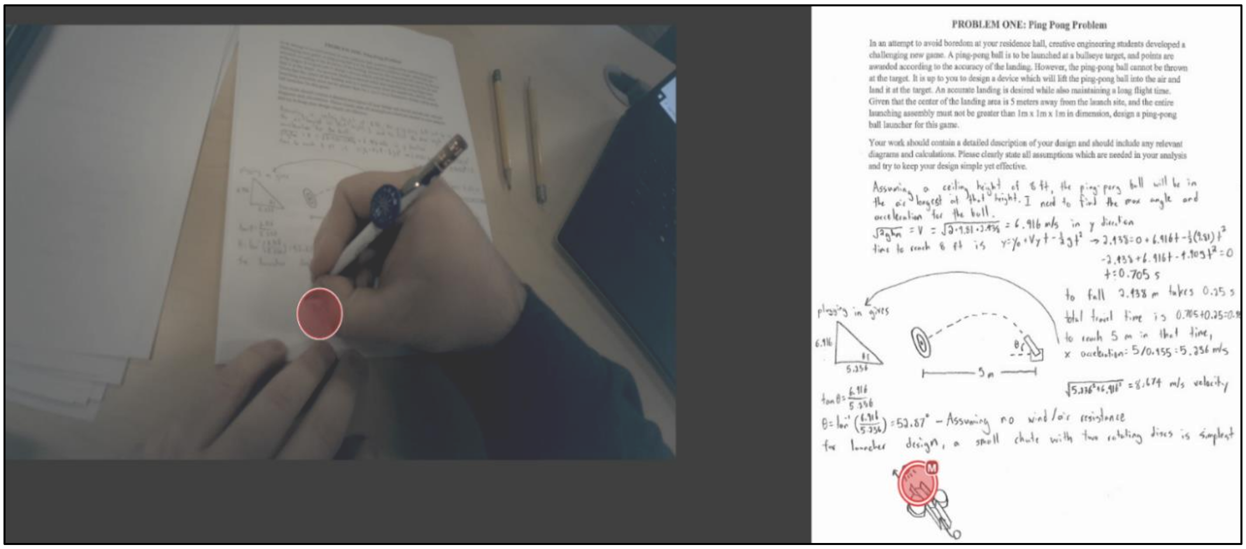


Figure 1: Tobii Pro Glasses
Image source: https://www.eyetracking.co.in/pdf/Tobii-Pro-Glasses3-Leaflet.pdf

optimal positioning [37]. It ensures an unobstructed view for the study participants. Additionally, the unit incorporates a Full HD resolution scene camera with a combined field of view of 106 degrees. The recording unit gathers eye-tracking data and wirelessly stores it on an SD card.
The participants solved the ping pong problem while wearing the eye-tracking device. Three types of data were collected i.e., 1) design problem artifacts created on paper, 2) video recording of the view direction of study participants via the camera in the glasses, and 3) gaze data were recorded throughout the problem-solving process.

4.4 Data Analysis

We utilized the Tobii Pro Lab software for analysis, leveraging its powerful tools tailored to meet various research needs, including data aggregation, interpretation, and visualization. Data recorded through the Tobii Pro Glasses 3 were imported to be analyzed in MP4 video format.



PROBLEM ONE: Ping Pong Problem

In an attempt to avoid boredom at your residence 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.

Assuming a ceiling height of 8 ft, the ping-pong ball will be in the air longest at that height. I need to find the max angle and acceleration for the ball.

$\sqrt{2gh} = V = \sqrt{2 \cdot 9.81 \cdot 2.438} = 6.916$ m/s in y direction

time to reach 8 ft is $y = y_0 + V_y t - \frac{1}{2} g t^2 \rightarrow 2.438 = 0 + 6.916t - \frac{1}{2}(9.81)t^2$

$-2.438 + 6.916t - 4.905t^2 = 0$

$t = 0.705$ s

to fall 2.438 m takes 0.25 s

total travel time is 0.705+0.25=0.9

to reach 5 m in that time,

x acceleration: 5/0.955 = 5.236 m/s

$\sqrt{5.236^2 + 6.916^2} = 8.674$ m/s velocity

plugging in gives

$\tan\theta = \frac{6.916}{5.236}$

$\theta = \tan^{-1}\left(\frac{6.916}{5.236}\right) = 52.87°$ – Assuming no wind/air resistance

for launcher design, a small chute with two rotating discs is simplest

Figure 2: Mapping participant eye movement data through an eye tracking software

As shown in the screenshot from the Tobii Pro Lab in Figure 2, for each fixation identified in the data recorded, a manual click was made by the researchers in the corresponding solution artifact. This process resulted in heat maps based on the number of visits (multiple fixations in a certain area) and fixations on a specific point (or areas) in the ping pong solution artifact (Figures 3 and 4) and the tracking of gaze paths between fixation points (Figures 5 and 6). The researchers met in person and online to conduct detailed qualitative examinations of the artifacts, heatmaps, and gaze plots. The qualitative examinations included observing the problem-solving behaviors of the study participants as demonstrated through their. For example, the number of images each participants made and how much text they used in their solutions were noted and analyzed. Heatmaps and gaze plots were also closely observed to understand the problems solving behaviors of the study participants.

To analyze the data, the gaze behavior was manually coded by reviewing the eye-tracking recordings and identifying specific events or areas of interest. This involved marking the onset and offset of fixations, saccades, or other relevant eye movements, as well as labeling the visual stimuli being viewed. Throughout the coding process, the Tobii Pro Lab software application provides tracking of the eye movement which was verified by making a "click" to mark the location. As can be seen in Figure 2, the participant's fixation is noted by the software (left part of the image) which was then verified manually showing the letter "m" with the red dot (right side of the image). This two-level eye-tracking process, first by the software application and then verified by the researchers contributed to the validity of the data analysis process.

5. FINDINGS

In this section, we discuss three findings obtained by comparing high and low spatial visualizers while they solved a ping-pong design problem.

5.1 Attention Paid to the Problem Statement vs Problem Solution

In all cases, the high visualizers paid more attention to the problem solution than the problem statement. By comparison, the low visualizers paid more attention to the problem statement than the problem solution. Denoted by red spots in Figure 4 (a and b), on the one hand, we observed that low visualizers read and re-read the problem statement. High visualizers on the other hand were observed to be able to retain the problem statement in memory and remain more in their problem-solution areas.

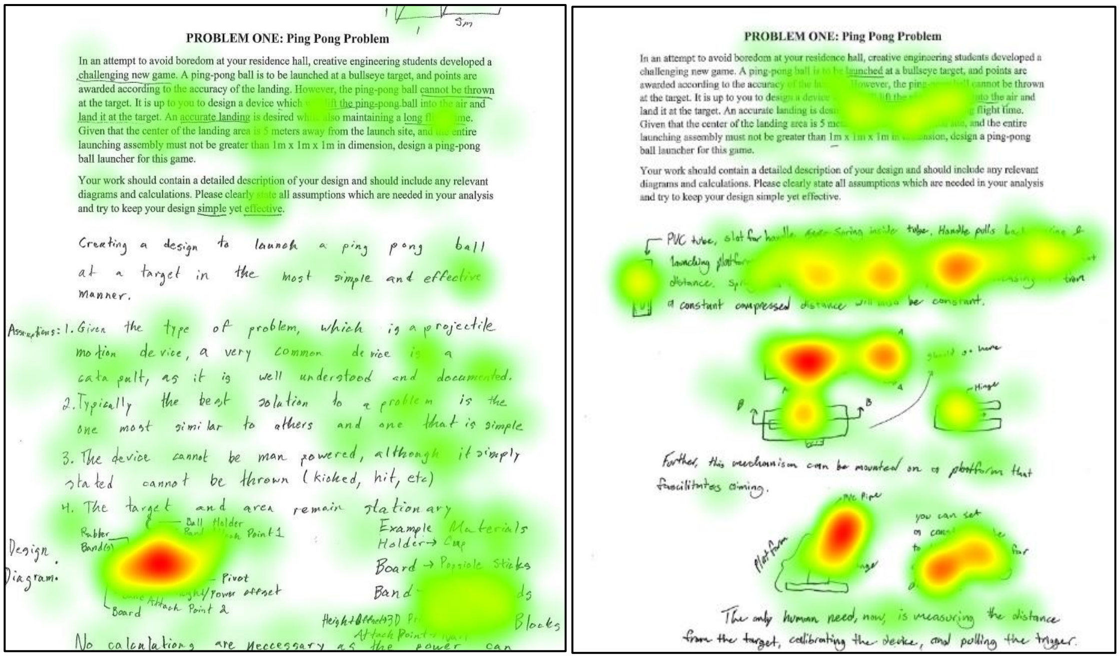
5.2 Toggling Between Problem Statement and Problem Solution

Consistent with the heatmap findings, the high visualizers, while focusing on their solutions, did not make frequent trips back and forth between the problem statement and problem solution areas. Low visualizers not only spent more time on reading and re-reading their problem statements but also made frequent trips back and forth to the problem statement while developing their solutions. The frequency of the back-and-forth trips is denoted by a rectangular area at the cutoff point between the problem statement and problem solution sections (denoted by rectangles on the plots)in the gaze plots in Figures 5 and 6. As can be seen in Figure 5 (a and b), the high visualizers are more consistent in focusing on the development of their solutions and do not spend much time going back to the problem statement.

Such a trend persisted in the majority (6/7) of the high visualizer participants. The majority (4/6) of low visualizer participants seemed to have divided attention as shown in Figure 6 (a and b). They are referring to the problem statement at an enormously higher rate compared to high spatial visualizers while developing their solutions to the design problem.

5.3 Developing Diagrams and Their Frequency

As can be seen in the problem statement of the ping pong design task (Appendix A), clear instructions were provided to the study participants to include any diagrams that they felt were necessary in their solutions. A count of the diagrams for all of the 13 solutions to the design problem produced by the study participants was made to examine if there were any differences between high and low spatial visualizers when it comes to creating sketches. Interestingly, high spatial visualizers created more diagrams compared to low spatial visualizers. On average, high visualizers drew 2 (14/7) diagrams compared to low spatial visualizers who averaged 1.5 (9/6).



(a) (b)

Figure 3. Heat maps of high spatial visualizers solving an engineering design problem

(a) (b)

Figure 4. Heat maps of low spatial visualizers solving an engineering design problem

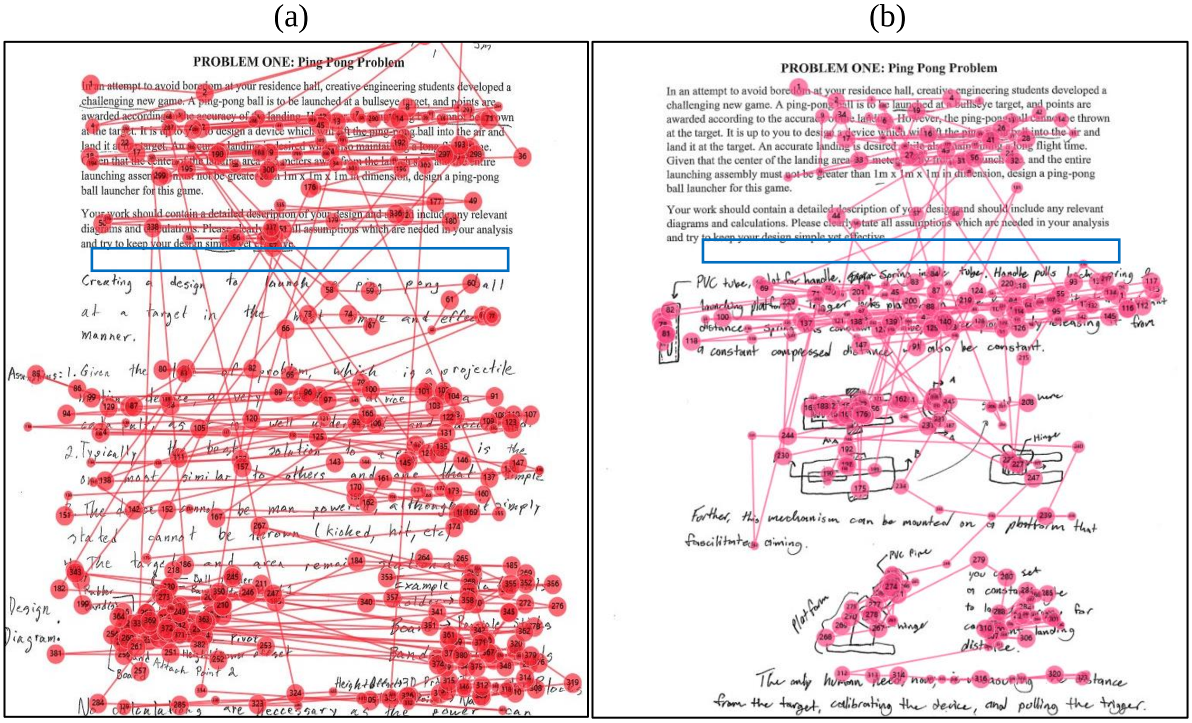


Figure 5. Gaze plots of high spatial visualizers solving an engineering design problem

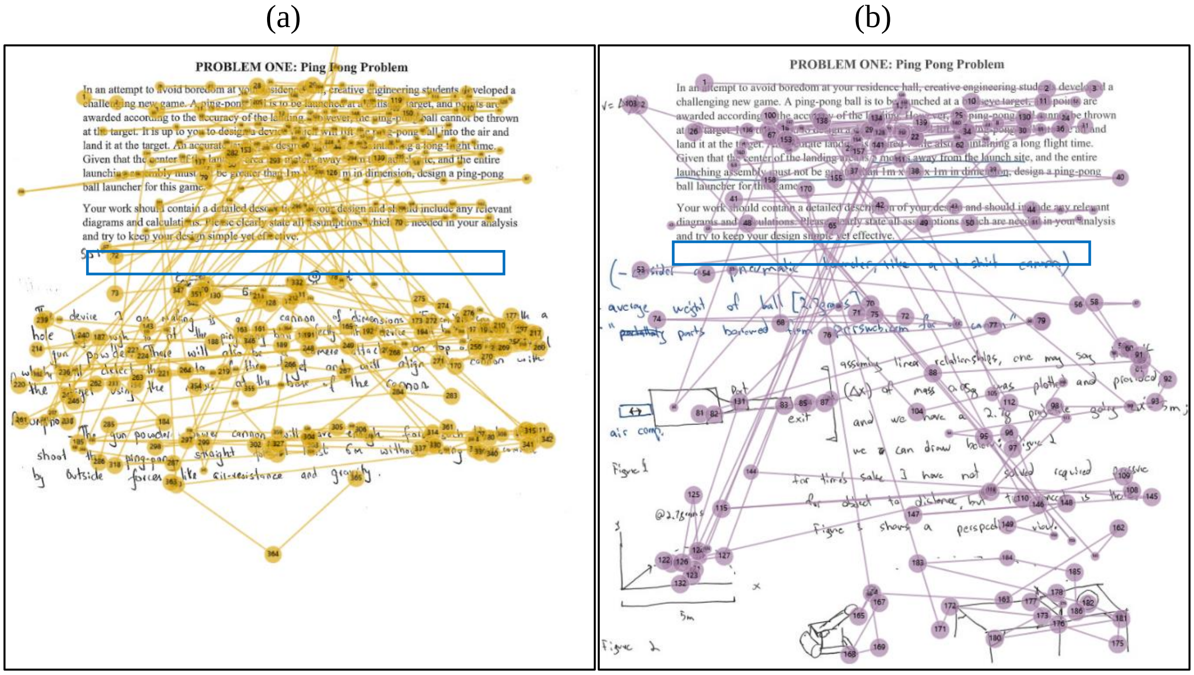


Figure 6. Gaze plots of low spatial visualizers solving an engineering design problem

There were also differences based on the focus and attention given to diagrams. Though it may appear from the sample heatmaps in Figure 3 vs Figure 4 that both high and low spatial visualizers paid attention to the diagrams, a close examination revealed that the focus of high spatial visualizers was more substantial, denoted by deep red spots on the diagrams in the heatmap. The red spots from the heatmaps on the diagrams by the low spatial visualizers were not as intense.

6. DISCUSSION

The findings from this study add to the literature suggesting differences between the design problem-solving mechanisms of engineering undergraduates with high and low spatial ability differences. We purposefully selected participant from their first and senior years. Interestingly, the differences in design problem-solving behaviors were due primarily to differences in spatial ability (high vs low) and not due to the year of study. A discussion of our results is provided as follows.

6.1 Utilizing "learning-while-solving" a design problem

High visualizers tended to build their design solutions based on their previous steps of the problem-solving process. Pribyl (1988) investigated problem-solving during stoichiometry questions and had similar findings [38]. Pribyl found the study participants with higher spatial abilities were able to utilize information generated during the previous problem-solving steps throughout their solving of the stoichiometry question prompts. Low spatial abilities participants were also inclined to make structural errors in their solutions [38]. This may imply that spatial ability may enhance the ability to retain and apply information throughout the problem-solving process.

6.2 Visualization of information

High visualizer participants in our study drew more diagrams and spent more time (i.e., fixated) on analyzing them compared to spending more time reading and re-reading the textual information in the problem statement as compared to low visualizers. Spatial ability plays an important role in learning from visualizations and should be considered as a crucial factor while designing visualization for academic learning purposes [39]. To support low spatial ability learners, visualizations might have to go through design modifications e.g., the "usage of 3d-visualizations", though an appropriate level of using such visualizations is controversial [39].

6.3 Concentration of attention in problem vs solution spaces

We observed that high spatial visualizing students when compared to low visualizers were spending more time in the solution spaces than they did in the problem statement spaces. This was denoted by clusters of fixations or the redness in the heatmaps (Figures 3 vs Figures 4). Low visualizers were also observed to make an unusually high number of trips between the problem and solution spaces (Figures 5 vs Figures 6). The unusually high number of back-and-forth trips between problem and solution spaces may denote a state of confusion among the low visualizers. Mohler (2007) suggests low spatial visualizers have a limited ability to simplify and break down spatial problems into cognitively manageable chunks [40]. Such an inability may consequently cause confusion and frustration which may dictate the unusually high number of trips between the problem and solution spaces in search of answers. This suggests that spatial ability influences how individuals allocate their attention during problem-solving tasks and may affect their ability to simplify and breakdown design problems into manageable chunks

7. IMPLICATIONS

There are several implications of this study for engineering educators. Many researchers have linked Spatial ability with student success in STEM [3-6]. Therefore, educators should consider tailoring instructional materials in their pedagogies. As this research suggested that students with higher spatial ability tend to prefer visual information, educators may use more visual aids and diagrams to support student success. However, the provision of information should not be limited to one or another form. Both textual and visual formats should be used to support students with diverse cognitive styles.

Recognizing the importance of spatial abilities in design problem-solving, educators can also incorporate activities and exercises aimed at developing spatial skills among students. This can include spatial reasoning tasks, visualization exercises, and hands-on design projects.

8. CONCLUSIONS AND FUTURE RESEARCH

Higher spatial visualization and design thinking capabilities are important in undergraduate engineering success. There is a scarcity of research examining these two constructs together. The current paper attempts to fill this gap by investigating the differences between undergraduate engineering students with high and low visualization skills by tracking their eye movement while they solve open-ended design problems. When compared with low visualizers, high visualizer participants focused more on the solution space vs the problem statement space and developed more diagrams with these diagrams being the focus of their attention.

Research relating spatial ability and design thinking is an emerging area of inquiry. Though our research provides some understanding of how the design problem-solving behaviors of undergraduate engineering participants differ based on their levels of spatial ability while, why such differences exist and how they might affect their learning outcomes is yet to be known. Future research provide us some insight into it.

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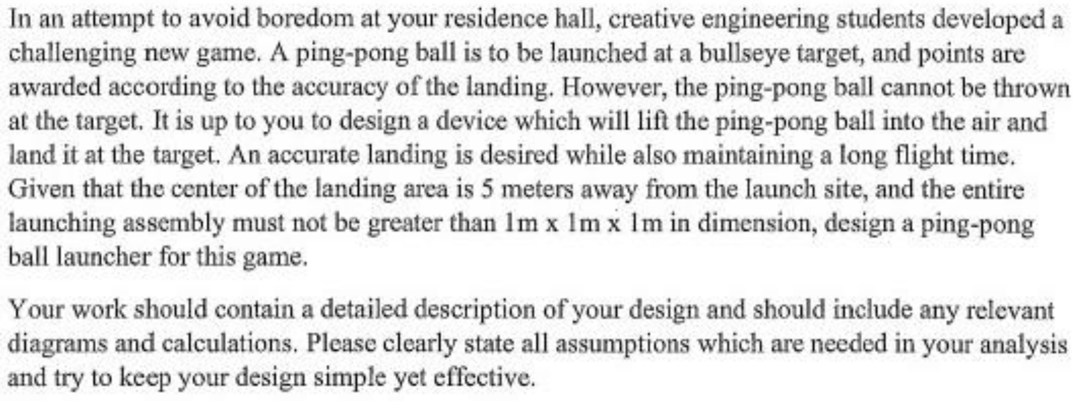
APPENDICES

Appendix A

Ping Pong Problem



In an attempt to avoid boredom at your residence 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.