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The Role of Spatial Skills and Sketching in Engineering Design Problem Solving

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ABSTRACT

Spatial visualization is the ability to mentally manipulate, visualize or transform objects in one's mind. Numerous research studies have reported that spatial ability is strongly associated with predicting success and retention in STEM-related fields such as math, engineering, computer programming and science. Spatial skills are a critical cognitive ability for many technical fields particularly engineering. Further, numerous studies have shown the importance of free-hand sketching in the development of 3-D spatial skills. Similarly, sketching is an integral component in the engineering design process, especially in the idea-generation phase. However, little work has been performed examining the link between spatial skills and the quality of sketches produced by undergraduate students during the engineering design process.

There were two phases of data collection for this research. In the first phase, 127 undergraduate engineering students completed four standardized tests of spatial cognition. In the second phase 101 students returned to complete three design tasks. This paper examines the performance of the 16 low spatial and 15 high spatial visualizers on one of these tasks. For this specific task, individuals are asked to design ways to catch and use rainwater in remote villages. Through analysis of the sketches produced by the students, initial insights indicate that there may be an association between the spatial skills of students and the quality of the sketches they produce for their engineering design solutions. These insights will be discussed relative to the potential influence of spatial skills and sketch quality on engineering education, specifically in developing design capability.

Key words: Spatial skills, sketching, engineering design, problem solving

Introduction

In the current evolving landscape of engineering and design education, the development of spatial visualization skills is viewed by many as a key to ensuring student success and competency. Spatial skills are crucial for grasping, manipulating, and projecting spatial relationships between objects, and are pivotal in understanding [1] and solving complex problems that involve spatial orientation and design [2, 3]. Such skills are indispensable in various fields, particularly in engineering, architecture, and various other STEM disciplines [4] [5] [6].

The engineering design process is profoundly visual in nature, involving the rendition of abstract concepts into tangible representations. Sketching plays a central role in this translation, which is an important skill for engineers. Sketching not only enables the communication of ideas but also is often considered an innate and structural form of expression that plays a significant role in problem-solving and conceptualization in technical fields such as engineering. However, with the rise of digital tools like computer-aided design (CAD) tools, the role of traditional sketching in fostering these skills has become a subject of keen academic interest.

The significance of spatial skills in engineering is well-established, as these skills are necessary for understanding sophisticated concepts and fostering innovative designs [7]. Traditional sketching has long been considered a fundamental tool for developing these abilities, allowing students to convey ideas, explore design options, and understand spatial relationships in a direct and immediate manner [8]. However, with the emergence of CAD tools, there has been a paradigm shift in how these skills are taught and developed. CAD offers precision and efficiency but often at the expense of the instinctive comprehension associated with freehand sketching [9].

Studies by Merzdorf et al. [10] and Contero et al. [11] have underscored the importance of sketching instruction in augmenting spatial skills, thereby improving students' overall design process in engineering education. This underlines the critical role of spatial visualization in sketch creation, indicating that experts in the field prioritize the shape quality metrics over line quality in sketches. This reflects the evolving nature of engineering education, where digital tools are increasingly employed to bridge the gap between spatial understanding and sketching proficiency.

Furthermore, incorporating sketching in engineering education has been revealed to boost spatial visualization skills [6, 12, 13]. This improvement is crucial, as it directly influences the quality of sketches, which in turn affects the efficiency and effectiveness of the engineering design process. Additionally, the capability to produce high-quality sketches is linked with improved problem-solving abilities [14] [15]. Recent research indicates that there is a correlation between spatial visualization and sketch quality in solving engineering mechanics problem; in these studies, it was reported that students with high MCT (a test of spatial visualization) scores had better sketches compared to students with lower levels of MCT scores [14]. This correlation is important because sketches are more than documentation tools, they are integral to the cognitive process of design, helping in problem identification, idea development, and solution assessment [16].

Research has shown that spatial visualization abilities are important for success in engineering design tasks. These studies highlight the existence of a connection between engineering design skills and spatial reasoning capabilities [17, 18, 19]. Although they did not directly address sketch quality, these studies highlight the broader relevance of spatial skills in the engineering design process. However, there still remains a gap in our understanding regarding how these skills are related to the quality of the sketches while solving engineering design tasks. Thus, this research paper aims to begin to explore the depth of this relationship using a mixed methods approach.

Methodology

In this research study, we used a sequential mixed methods approach to examine the relationship between spatial skills and the quality of sketches produced by students as they completed an open-ended design task. This mixed methods research methodology uses two different strands i.e., the quantitative strand, where numeric data are collected and analyzed followed by a qualitative strand, in which textual data are collected and analyzed sequentially and combined to provide inferences [20]. This research method was used to deliberately select participants for the qualitative phase using quantitative data instead of random choice. This approach helps in interpreting the quantitative findings through a qualitative context [21]. In subsequent analyses, the data will be combined to yield insights that will help us understand the relationship between spatial visualization skills and sketching [20].

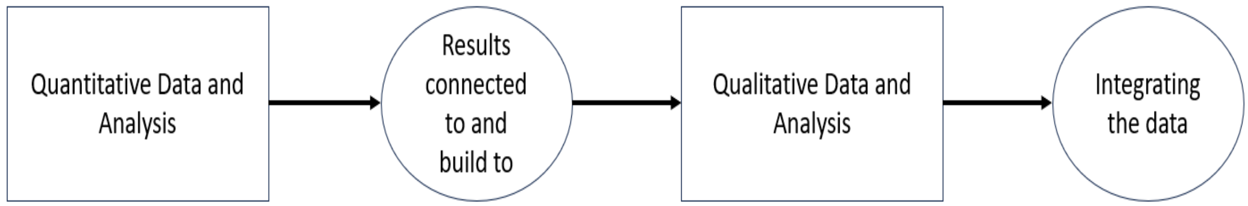

Figure 1: Sequential Mixed Methods Design

Setting and Participants

The present study was conducted at a public R1 university within its College of Engineering and Applied Science. The study involved engineering students from both their first and final years of study in their respective programs. Participants were recruited by distributing flyers across the college. The research was carried out with the approval of the university's Institutional Review Board.

Quantitative Data Collection

During the quantitative phase of the research, 127 undergraduate engineering students were supervised by a research assistant as they completed four well-known spatial ability tests online. These tests were the Mental Cutting Test (MCT) [22], the Mental Rotation Test (MRT) [23], the Paper Folding Test (PFT) [24], and the Spatial Orientation Test (SOT) [25]. Additionally, a verbal analogy test was administered as a measure to control for general intelligence; however, the results from the verbal analogy test were not used in the data analysis for this paper. Following the completion of these tests, the students' scores were used to categorize them into three groups based on their spatial visualization skills: high, medium, and low.

Qualitative Data Collection

Out of the initial participants, 31 (15 high and 16 low spatial) participants were purposively sampled for the second phase of the study, which involved concurrent verbal protocols while completing various design tasks [26]. Furthermore, maximum variation sampling was utilized to capture the widest range of responses from the high and low spatial visualizers. In this phase, each participant was tasked with solving three open-ended engineering design tasks [17]. However, this study will focus exclusively on one specific problem: developing multiple solutions for a remote village where access to fresh clean drinking water is very limited. The complete problem statement for this design task is in Figure 2.

PROBLEM THREE: Remote Village Rainwater Catcher

In remote villages throughout many rural, underdeveloped areas of the world, easy access to fresh clean drinking water is very limited. Villagers must often walk long distances to a fresh water source, collect the water in large, awkward bins, and then carry the water back uphill to their home. Retrieving fresh drinking water in this manner takes tremendous amounts of time and effort. In many cases, however, rainwater is a fresh and abundant source of water, but there are no solutions for effectively capturing, storing, and distributing the water.

Design ways for remote villagers to catch and use rainwater. Your solutions should focus on creating totally new designs or developing totally new ways of approaching the problem. Don't be concerned about a particular cost or size of your solution, and feel free to choose any materials you desire, as those sorts of constraints might be able to be worked out in the future.

Develop multiple solutions for this problem. Focus on developing radical solutions. Try to develop solutions without concern for cost or immediate workability. Be sure to write each solution on a different piece of paper and use drawings as necessary to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.

Figure 2: Snapshot of the Remote Village Rainwater Catcher

For the second phase of the research study, participants were in a distraction-free room within the college, creating a peaceful environment for test-taking. With the participant's consent, all sessions were video recorded. Upon completion of the design task by the participants, their responses were analyzed using a coding system created by the researcher. The focus of this paper will be on the "Understandability" aspect of the design which is crucial for understanding the quality of the sketches produced by the students. This aspect, derived from Das and Young's work [27], was adapted by the researcher to a 1-4 scale so that the understandability scale matched other quality metrics used to evaluate the solutions (note that these other quality metrics are not considered in this paper). The understandability scale and its associated description for assessing the sketch quality are tabulated in Table 1. The overall "*Understandability"* dimension is defined as "the degree to which the idea is clearly represented with figures".

The quality of the sketches of the design solutions for each participant was coded by two independent coders. They ensured interrater reliability by achieving a 95% agreement rate on their assigned codes. Discrepancies were resolved through discussion until unanimous agreement was reached for each participant. The interrater reliability was quantified, resulting in a Cohen's Kappa value of 0.94, indicating a strong consensus between the coders.

Table 1: Understandability Metric

Understandability	
Score	**Description**
4	Sketch is perfectly clear, and it can be understood without explanation.
3	Sketch is generally clear, but some details are confusing.
2	Can recognize the shapes from the sketch but hard to recognize what it means.
1	Cannot guess what the sketch means or no sketch.

Results

In the quantitative phase of this research study, the researcher graded spatial ability tests using Excel, after transferring the data from Qualtrics. The participants included 127 undergraduate engineering students, consisting of 42 Females and 85 Males. The internal consistency reliability of each of the four tests was evaluated. The KR20 and Cronbach's alpha value for all the spatial tests were above 0.80, except for the Spatial Orientation Test (SOT), which had a KR-20 value of 0.65. This score is typically considered to be indicative of satisfactory internal consistency reliability, as noted by El-Uri and Malas [28]. To categorize the participants into high and low spatial groups, a principal component analysis was carried out [29]. After running the PCA, two principal components were generated. The first principal component (83.5%) met the criteria of explanatory power of exceeding 80%. Participants were divided into three groups based on the first principal component: low, medium and high spatial visualizers. However, this study focused only on the participants with either high or low spatial skills. Table 2 presents a summary of the spatial scores for these two groups. It includes the average scores and standard deviations for each group, with the maximum possible score being 81.

Table 2: Spatial Scores – Average and Standard Deviation

Spatial Scores	
Low Spatial Visualizer (n=16)	
Avg. Score	23.63
Std. Dev	5.39
High Spatial Visualizer (n=15)	
Avg. Score	61.2
Std. Dev	5.80

In the qualitative phase, we used the "Understandability" metric to evaluate the sketches that were produced as part of assessing the concepts generated through the design task. After coding all the sketches based on the "*Understandability"* metrics, the scores of each design were calculated and were averaged for the number of designs per person. The average scores of high and low spatial groups were then calculated and are tabulated in Table 2. It was determined that high spatial visualizers had better average scores on their design sketches compared to low visualizers. To understand if the differences were statistically significant, we ran an independent sample t test. This study found that low spatial visualizers had statistically significantly lower understandability score when solving an open-ended engineering design task compared to high spatial visualizers, $t(31) = -2.641$, $p = 0.006$.

In this current study, we employed purposive sampling to select specific participants for detailed analysis. This section included data from 16 participants who were identified as low spatial visualizers (comprising 6 Females and 10 Males) and 15 who were identified as high spatial visualizers (2 Females and 13 Males).

In our research, we conducted a correlational analysis to explore the association between spatial abilities and sketching proficiency. This involved examining the relationship between participants' individual spatial scores and their scores on the Understandability metric. The findings, detailed in Table 3, reveal that there is a positive correlation between the spatial scores and the Understandability metric scores, df = 31. Furthermore, the analysis indicates a strong positive correlation among all four spatial scores themselves. This suggests a significant interrelation between different aspects of spatial abilities and their collective impact on sketching proficiency. Figure 3 shows example sketches produced by a low and a high spatial visualizer who had only one solution for the problem. Figure 3a is a sketch that was developed by a low spatial visualizer who has an understandability score of 1. This indicates that the figure is not clear and therefore cannot be in a position to easily draw meaning of the proposed solution. Conversely, figure 3b shows a sketch by a high spatial visualizer with an understandability score of 4 indicating a clear and detailed working description of the intended solution. Similarly, you can observe a similar response pattern for students with similar understandability scores but with two solutions. From the data, it was observed that low spatial visualizers struggled to convey their ideas through sketches and the working of the solutions.

Table 3: Correlation Co-efficient Table

	Total MRT	**Total MCT**	**Total FT**	**Total SOT**	**Total Spatial Scores**
Total MCT	0.566^{**}				
Total FT	0.689^{**}	0.712^{**}			
Total SOT	0.645^{**}	0.802^{**}	0.742^{**}		
Total Spatial Scores	0.825^{**}	0.820^{**}	0.883^{**}	0.799^{**}	
Understandability	0.462^{**}	0.440^{*}	0.424^{*}	0.497^{**}	0.511^{**}

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

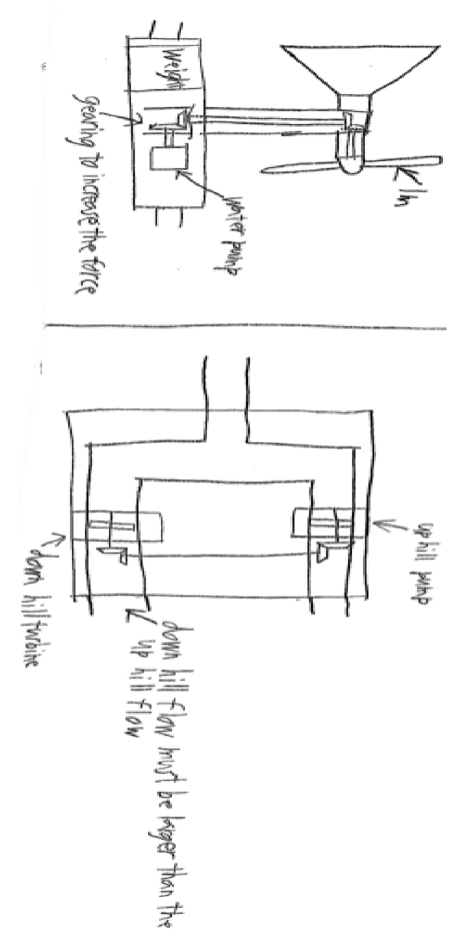

Figure 3: a) Snapshot of the sketch drawn by a low spatial visualizer (left); b) Snapshot of the sketch drawn by high spatial visualizer (right).

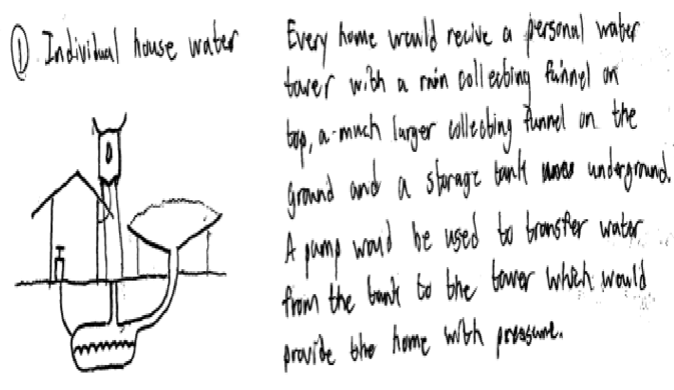

Figure 4 : a) Snapshot of the sketch drawn by a low spatial visualizer (left); b) Snapshot of the sketch drawn by high spatial visualizer (right).

Discussion and Conclusion

The engineering education academic community broadly agrees on the critical role of spatial skills in engineering success. However, there is a notable gap in research exploring the link between sketching ability and spatial ability. In alignment with this identified research need, as discussed earlier in this paper, our investigation focuses on understanding how spatial abilities influence the quality of sketches produced by undergraduate engineering students when completing open-ended tasks. This study aims to contribute to the body of knowledge by examining this specific aspect of engineering education and practice.

Our findings indicate that students with higher spatial visualization abilities tend to create better, more understandable, freehand sketches. Moreover, our correlational analysis supports a positive relationship between spatial skills and sketch quality. Future research could focus on how this relationship varies with factors such as the students' year in the program, gender, previous design experiences and their subsequent impact on sketch quality. This data presented here represents the first year of a two-year investigation of a larger project, and further data from the second year is anticipated to enhance our understanding and potentially corroborate these initial findings. This research contributes valuable insights into the relationship between spatial skills and sketch quality in engineering education. Such insights have the potential to inform and improve educational strategies aimed at developing spatial abilities in engineering programs, thereby enhancing overall student success in this field. These insights can inform program designers regarding how they may adjust their curricula to incorporate more deliberate spatial training and sketching practices.

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