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Enhancing Visualization Skills in Engineering Education Using Virtual and Augmented Reality Environment

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Abstract
This study explores the impact of Virtual Reality (VR) and Augmented Reality (AR) on enhancing visualization skills in engineering education, a crucial competency for understanding complex engineering drawings. A quasi-experimental design with non-equivalent control groups was employed, involving 90 first-year engineering students divided into three groups: VR, AR, and a conventional teaching method control group. The Purdue Spatial Visualization Test for Rotation (PSVT:R) was used to assess students' visualization skills before and after the intervention. Results showed that while the experimental groups started with higher initial visualization abilities. VR and AR methods led to significant declines in post-test scores, indicating potential cognitive overload from navigating these advanced technologies. In contrast, the control group showed no significant change, underscoring the limitations of traditional methods. The findings suggest that the current implementation of VR and AR may not effectively support visualization skill development without proper instructional scaffolding. A blended approach, integrating conventional and technology-based instruction with appropriate cognitive support, is recommended to optimize learning outcomes. This study highlights the need for careful integration of emerging technologies into engineering curricula to enhance education quality and meet the demands of modern engineering practices.
Keywords: Virtual Skills, Engineering Education, Virtual Reality, Augmented Reality, Engineering Drawing

Introduction

The technology has profoundly transformed various aspects of our daily lives, becoming a foundation in fields such as engineering education. One of the most significant developments in this area is the integration of technology to enhance the learning experience (Ahmad et al., 2025). Over the past century, educational institutions have increasingly adopted technological tools to support and improve the pedagogical process (Froyd et al., 2012). This trend is particularly evident in engineering education, where the importance of design courses has grown steadily due to the critical role design plays in shaping engineering competencies (Brunhaver et al., 2017). In engineering programs, 1st year students are typically required to take engineering drawing courses. Engineering drawing provide a foundational understanding of engineering design principles. These courses aim to develop essential skills such as spatial visualization, which is the ability to interpret and manipulate 2-Dimensional (2D) images and 3-Dimensional (3D) objects (Ali et al., 2024). Mastery of these skills is crucial for students' academic performance and their future professional success (Ali & Mokhtar, 2014). However, many students face challenges in developing visualization skills, which often negatively impact their understanding and ability to apply engineering concepts. Studies have shown that difficulties in visualizing objects are a common issue among students (Baronio et al., 2016). That is potentially impaired by a growing dependency on digital devices that may impair perceptual skills.

Visualization skills are integral to engineering education as they enable students to rationally manipulate objects and understand complex processes across various scales and disciplines (Shamsuddin & Che Din, 2016). Research has indicated that 1st year engineering students often possess only moderate visualization skills, particularly in mental rotation, a key component of spatial visualization skills critical for technical drawing and problem-solving in engineering (Ali et al., 2016). Engineering students must create technical drawings during their coursework, which involves three processes based on McKim's Visual Thinking Model (McKim, 1980), as shown in Figure 1. Traditional teaching methods, such as static diagrams and conventional lectures, may fall short in effectively conveying these concepts. Thus, necessitating the exploration of alternative educational tools and strategies (Khabia & Khabia, 2012; Mackenzie & Jansen, 1998). In response to these challenges, educators and researchers have explored various approaches to enhance visualization skills in engineering students. With the advent of the Fourth Industrial Revolution (4IR), there has been a marked shift towards utilizing advanced technologies such as virtual reality (VR) and augmented reality (AR) in educational settings (Alotaibi, 2021; Mokgatla & Moseley, 2020). These immersive environments provide interactive, 3D spaces where students can actively engage with the material, promoting self-exploration and deeper understanding (Sorby, 2009). Unlike traditional teaching methods, VR and AR offer dynamic and interactive learning experiences that can significantly improve students' spatial awareness and visualization skills (Papanastasiou et al., 2019).

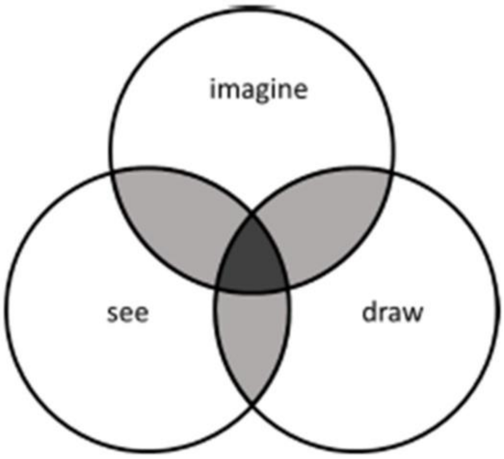

Fig.1 Model of visual thinking by McKim (1980)

The potential of VR and AR in engineering education is substantial. These technologies can bridge the gap between theoretical knowledge and practical application by enabling students to visualize complex engineering concepts in a more intuitive and engaging manner (Davila Delgado et al., 2020). Moreover, they cater to the motivational needs of learners, such as the desire for exploration, manipulation, and active engagement, which are essential for effective learning (Krapp, 1999). By providing a more stimulating and interactive learning environment, VR and AR not only enhance students' visualization skills but also foster creativity and critical thinking (Papanastasiou et al., 2019; Sanabria & Arámburo-Lizárraga, 2017). The integration of VR and AR into engineering education offers a promising solution to the limitations of traditional teaching methods (Alvarez-Marin & Velazquez-Iturbide, 2021). As educators continue to seek innovative ways to improve teaching and learning, the adoption of these technologies has the potential to revolutionize the way engineering concepts are taught and understood, ultimately preparing students for success in a rapidly evolving technological landscape.

Methodology

This study employed a quasi-experimental design with a non-equivalent control group to evaluate the effectiveness of 3 different teaching approaches in enhancing the visualization skills of 1st year engineering students. The participants of this study were 90 students, divided into three groups of 30 students each. 2 experimental groups (Group A and Group B) were exposed to technology-based instructional methods. Group A was exposed to VR-based learning, and Group B to AR-based learning. While the control group (Group C) received traditional teaching methods. The Purdue Spatial Visualization Test for Rotation (PSVT:R) was used as the assessment tool to measure students' mental rotation abilities before and after the intervention. To ensure comprehensive data collection, pre-test and post-test questionnaires were used from all participants. The questionnaires assessed not only their visualization skills but also their learning interest and satisfaction. Descriptive statistics were used to summarize the data. Even though inferential statistical analyses were conducted to compare the pre-test and post-test scores across the groups. It determines the effectiveness of each instructional method. The analysis aimed to identify any statistically significant improvements in visualization skills and evaluate the students' perceived interest and satisfaction with the learning experience. This methodology provides a structured approach to exploring the potential of VR and AR environments in enhancing visualization skills within engineering education.

Results and Analysis

The primary objective of implementing technology in engineering drawing classrooms is to facilitate students' visualization skills development and enhance their interest in learning. This approach aims to optimize the learning transfer process and reduce the cognitive load during the learning experience. Table 1 shows PSVT:R pre-test scores comparison of 2 experimental groups and a control group.

Table 1
PSVT:R Pre-Test Scores Comparison

Test	Group	N	Mean Scores	Standard Deviation
PSVT:R	A - Virtual Reality	30	61.333	7.608
	B - Augmented Reality	30	58.667	25.151
	C - Conventional Method	30	-0.8893	31.983

Table 1 presents the pre-test scores from the PSVT:R for 3 groups of 1st year engineering students. Group A, exposed to the VR approach, had the highest average pre-test score of 61.333 with a standard deviation of 7.608. It indicates relatively strong initial visualization skills and low variability among students. Group B, using the AR approach, shows a slightly lower mean score of 58.667 with a standard deviation of 25.151. It suggests that while their average visualization skills were comparable to Group A, there was greater variability in their abilities. In contrast, Group C, which followed the conventional method, had a negative mean score of -0.8893 with a standard deviation of 31.983. It reflects very low initial visualization skills and high variability among the participants. These pre-test results suggest that students in the experimental groups started with higher visualization abilities compared to the control group, which demonstrated significantly lower skills prior to any instructional intervention.

Tables 2 shows PSVT:R pre-test and post-test for the VR, AR, and conventional methods highlight the differences between the mean scores.

Table 2
Differences between Mean Psvt:R Pre-Test And Post-Test Scores

Group	PSVT:R Pre-Post		
	Mean	t	Sig. (2-Tailed)
A - Virtual Reality	-9.000	-3.395	0.002
B - Augmented Reality	-23.778	-4.417	0.000
C - Conventional Method	-1.066	-0.236	0.815

Table 2 illustrates the differences in mean scores between pre-test and post-test results for 3 groups of students. The mean score differences indicate how much each group's visualization skills changed after the intervention, while the t-values and significance (Sig. 2-Tailed) values show whether these changes are statistically significant. For Group A, the mean difference is -9.000, with a t-value of -3.395 and a p-value smaller than the α value ($p = 0.002 < 0.05$). Group B had a mean difference of -23.778, with a t-value of -4.417 and a p-value smaller than the α value ($p = 0.000 < 0.05$). The p-value indicates a statistically significant decline in visualization skills after the VR and AR interventions. Group C shows a mean difference of -1.066, with a t-value of -0.236 and a p-value greater than the α value ($p = 0.815 > 0.05$). Group C is not statistically significant, suggesting that the conventional teaching method did not cause any meaningful change in visualization skills. The results indicate that both the VR and AR methods resulted in significant declines in student performance, as shown by their p-values being less than 0.05, while the conventional method showed no significant effect.

Discussion

The results from Table 1 and Table 2 highlight significant challenges in developing visualization skills among engineering students using technology-enhanced methods such as VR and AR. In the context of engineering drawing, which requires students to accurately interpret and create complex representations of 3D objects in 2D space, strong visualization skills are crucial (Sorby, 2009). The pre-test scores in Table 1 show that students in the experimental groups started with a relatively higher baseline in visualization skills compared to the control group. It reflects potentially better initial experience ability for these skills. However, the high variability observed in the AR technology suggests that not all students were equally prepared to benefit from this technological intervention (Garzón et al., 2019), which could pose a challenge in uniformly improving skills across a diverse student cohort. The low initial scores of the control group underline the difficulties many students face when approaching engineering drawing tasks without advanced instructional support, indicating a need for innovative teaching strategies (Silva & Agostinho, 2018; Ngatiman & Saud, 2023).

Despite the promising baseline, Table 2 reveals that both VR and AR interventions led to a statistically significant decline in pre-test and post-test, different from expectations. This suggests that while these tools have the potential to enhance learning (Huang et al., 2021). The complexity of navigating virtual environments or the novelty of the technology could have imposed additional cognitive load, delaying rather than supporting skill achievement (Chang, 2024). This finding is particularly relevant in engineering education, where the ability to mentally manipulate and understand spatial relationships is integral not only to engineering drawing but to broader problem-solving and design tasks. The lack of improvement, and indeed the decline in performance, raises critical questions about how these technologies are integrated into the curriculum and whether students are adequately prepared to utilize them effectively (Abich et al., 2021; Fominykh et al., 2020).

These results suggest that simply incorporating advanced technologies into engineering education is insufficient for enhancing visualization skills. There is a need for a more structured approach to integrating VR and AR, one that includes scaffolded instruction and cognitive support to help students gradually build their visualization skills. Educators should consider the cognitive load imposed by these technologies and adapt their teaching methods to ensure that the tools serve to enhance, rather than overwhelm, students' learning experiences. The traditional methods, as seen in the control group, did not produce significant improvements. It indicates that a blended approach, combining conventional methods with carefully designed technological interventions, may be necessary (Kaplan et al., 2021; Liberatore & Wagner, 2021). This approach could better support the development of visualization skills crucial for success in engineering drawing and the broader field of engineering education.

Conclusion

The implementation of technology in teaching and learning should be fully involved in accordance with the curriculum's demands. It can facilitate a deeper understanding of subjects and enable students to develop their spatial visualization skills while also enhancing their motivation to learn. However, the findings of this study indicate that while advanced technologies like VR and AR have the potential to enhance learning. The current integration in engineering education may not be effective without proper instructional design. Despite higher initial visualization skills, students exposed to these technologies experienced a significant decline in performance. It suggests that the complexity of VR and AR may impose additional cognitive load. However, conventional methods did not produce significant improvements, highlighting their limitations in fostering visualization skills. This highlights the need for a blended approach, combining traditional and technology-based instruction with scaffolded support to optimize learning outcomes. Educators must move beyond the familiarity of conventional methods and continuously seek the most appropriate teaching strategies that align with technological advancements and societal needs. Therefore, educators can enhance the quality of education in Malaysia and elevate it to the standards of developed countries, fully leveraging the potential of technology to meet the demands of 21st-century education.

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