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Enhancing Student's 3D Development and Mental Rotation Skill using Augmented Reality

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Abstract

The increasing importance of augmented reality (AR) environments in education highlights their potential to enhance students' mental rotation abilities and 3-Dimensional (3D) visualization skills, particularly in engineering drawings. Enhancing these skills is crucial to understand and interpret complex engineering drawings concepts effectively. Therefore, this study was conducted to identify the effects of AR-based learning environments on students' mental rotation abilities and 3D visualization skills in engineering drawing education. This study employed a quasi-experimental design with a treatment group engaged in immersive AR-based sessions, whereas the control group received traditional instruction. Both groups were assessed using the Purdue Spatial Visualization Test for Rotation (PSVT:R) and the Purdue Spatial Visualization Test for Development (PSVT:D) before and after the intervention. The analysis methods for both the experimental and control groups included paired sample statistics and paired differences to evaluate pre-test and post-test scores. The findings indicated significant improvements in the treatment group's mental rotation and 3D development skills compared to the control group. Specifically, the AR environment facilitated a substantial increase in PSVT:R and PSVT:D scores, demonstrating the effectiveness of AR in enhancing the spatial visualization skills crucial for engineering education. This study suggests that integrating AR technology into educational practices can significantly improve learning outcomes and, offer valuable insights for educators and instructional designers. Further research should explore the long-term effects of AR-based learning and its applicability across different engineering disciplines to maximize its educational potential.

Keywords: 3-Dimensional Development Skills, Mental Rotation Skills, Visualization Skills, Augmented Reality, Engineering Drawing

Introduction

Engineers study engineering drawings in university engineering programs. Such engines have developed a foundation for transforming theoretical engineering models into technical designs and documents (Lin et al., 2021; Pan & Zhang, 2021). This course cultivates in its students those particular skills that allow the transmission of complex engendering notions by means of elaborated drawings that ultimately rock the house when it comes to different fields in which a soundly capable engineer can design, analyze, and innovate (Leake & Borgerson, 2019; Omar & Ali, 2018). Regarding the formation and visualization of visualization ability, generalized from the results of the literature research, engineering students have difficulty understanding engineering drawings in terms of schematization concepts (Jiang & Pang, 2023). Many students have difficulty properly manipulating and comprehending 3-Dimensional (3D) objects and ideas into 2-Dimensional (2D) forms. This may limit their ability to generate and understand engineering drawings, thereby affecting their performance in design, analysis, and communication in the field of engineering (Fujita et al., 2020; Hain & Motaref, 2020; Safaan, 2023). These obstacles must be overcome to ensure that engineering students acquire the necessary visualization skills to excel in their studies and careers.

Engineering Drawing is based on the visualization and manipulation of objects in the mind; to visualize the object, one should be able to perform mental rotation (Kadam et al., 2021). Moreover, some students face problems when trying to mentally rotate complex geometrical figures or imagine the connection between different views of an object, which can make it harder to produce high-quality technical drawings (Bartlett, 2024; Dere & Kalelioglu, 2020; Zhou et al., 2022). In addition, converting a 3D object into a 2D drawing or a 2D drawing into a 3D shape is a substantial challenge for engineering students (Totuk et al., 2023). The ability to represent physical elements and structures in drawings using orthographic projections, isometric views, parallel renderings, and section views guarantees precision (Giesecke et al., 2023; Kadam et al., 2024). These practices, when difficult to implement, deteriorate in drawings and do not merely imply clarity and accuracy. If these projections are misinterpreted, they can create problems in design and difficulties in the construction stages; hence, it is important to understand this concept in engineering drawings.

Engineering programs are also interdisciplinary, meaning that drawing skills are needed across disciplines, each with its own requirements and expectations. Sadly, mapping from one drawing standard, terminology, and all other conventions to another can be very difficult for the human mind to keep track of and prone to errors and misunderstandings (Beemt et al., 2020; Mursid et al., 2021). These results suggest the need for extensive education and support to enable students to adequately address this critical area and use it in their careers later on (Chan, 2023). Engineering drawings are examples of teaching subjects in which augmented reality (AR) has provided a more interactive and interesting learning experience (Iatsyshyn et al., 2020; Kumar et al., 2021; Liu et al., 2024). For Engineering Drawing education in AR environments, students can visualize such 3D-complex structures through 2D drawings, creating a link between theoretical aspects and practice (Alvarez-Marin and Velazquez-Iturbide, 2021; Tiwari et al., 2024). AR adds digital information to the physical world and creates a concrete and live ambiance that simplifies abstract thinking and understanding within the learning process (Al-Ansi et al., 2023; Alzahrani, 2020). A significant benefit of applying AR to engineering drawings is the improvement in spatial visualization skills (Schiavi et al., 2022). AR technology can enhance the teaching and learning process, making it more enjoyable and stimulating student interest in learning (Sazly et al., 2020; Sazly et al., 2021). This allows students to interact with 3D models in real-time, providing them with a better understanding of engineering principles that are often deemed difficult to understand through conventional 2D drawing methods (Fraile-Fernandez et al., 2021; Kadam et al., 2021). Figure 1 shows the 3D model for the isometric projection of the component, including its dimensions.

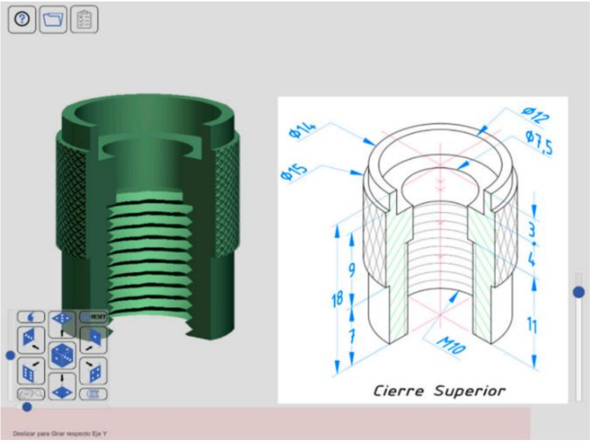

Fig. 1 Isometric projection of the component including dimensions (Fraile-Fernandez et al., 2021)

In addition, AR provides interactive learning in drawing and engineering (Juan et al., 2018). In this virtual realm, students can work together to design and instantaneously revise drawings, thereby nurturing teamwork and mutual learning (Wu et al., 2023). Learning happens by being exposed to how other students view and approach problem-solving. Moreover, AR aids in the teaching of engineering drawings using AR technology, which can address multiple learning styles, especially visual learners, by making the abstract come to life (Ibáñez & Delgado-Kloos, 2018; Liono et al., 2021). This multimodal style of learning adds to an inclusive atmosphere, which in turn allows students to study in a way that meets their preferences and enhances their overall engagement. AR is increasingly embraced by scenes and advanced technologies (Ansari et al., 2023). Students will gain a competitive edge by knowing AR tools, being able to tackle modern engineering challenges, and learning in an environment that is natural for commercial applications. Using AR is an incredibly valuable tool because of its immersive and interactive nature, the fact that it can be interactive in virtually no time, and the fact that it can be flexible enough to cater to many different learning styles, especially in engineering education (Childs et al., 2023; Selvakumar & Sivakumar, 2023).

Methodology

This study was conducted with first-year engineering students at Universiti Teknologi Malaysia, who were divided into two groups: an experimental group and a control group. The students in the experimental group participated in an AR learning environment, whereas those in the control group received conventional instruction. Both groups comprised 30 students. Students' visualization skills were tested before and after the intervention using the Purdue Spatial Visualization Test for Rotation (PSVT:R) and the Purdue Spatial Visualization Test for Development (PSVT:D). Data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 27.

The AR learning environment was built using Aurasma, Autodesk 3D Studio Max and AutoCAD. This technology adopted marker-based AR offered through the Aurasma app, which students used to scan markers and view 3D objects that had been created using AutoCAD. The 3D objects were designed using the AutoCAD software and processed on the Aurasma platform. The rationale for selecting Aurasma was its ready accessibility and ease of use for those without programming skills.

This tool is used under the philosophy of Constructivist Learning, in which students are actively involved in the learning process and lecture roles as facilitators (Kudryashova et al., 2015). The result is a learner-centered environment in which students can pace their learning. The teaching and learning tools were designed using the ADDIE Model. Examples of the augmented 3D objects used in this study are shown in Figure 2.

Fig. 2 Augmented 3D objects

Result and Discussion

Spatial skills, such as mental manipulation skills to visualize 2D and 3D objects, are vital for spatial reasoning and visualization, particularly in engineering and architecture (Lin & Chen, 2016; Shepard & Metzler, 1971; Lin & Yan, 2024). Extent to which mental rotation and 3D development skills are affected by exposure to an AR learning environment. This study aimed to review pre-test and post-test performance scales in mental rotation and 3D development skills to determine the impact of AR-based learning tools.

A. Mental Rotation and 3D Development Skills using AR Learning Environment

AR is an educational solution tool for enhancing mental rotation and 3D development, both of which underpin problem-solving and innovation in multiple industries (Sharma & Mantri, 2019). After completion of AR learning, the experimental group was given post-tests on mental rotation and 3D developmental skills.

The respondents' performance on the PSVT: R post-test assessed improvement in mental rotation skills in the experimental group. The hypotheses of this study are as follows:

H_o: There was no significant difference in the ability of the experimental group to mentally rotate the 3D objects.

Tables 1 and 2 display the results of the paired sample statistics and paired differences for the PSVT: R pre-test and post-test scores in the experimental group trained in an AR learning environment.

Table 1
Paired samples statistics of PSVT: R using AR learning environment

	Mean	N	Std. Deviation	Std. Error Mean
PSVT: R PRE	58.668	30	25.151	4.592
PSVT: R POST	82.444	30	15.109	2.758

Table 1 presents the paired sample statistics for the differences between the mean scores of the PSVT: R pre-test and post-test in the experimental group. The mean score increased from 58.668 (SD = 25.151) in the pre-test to 82.444 (SD = 15.109) in the post-test. This indicated a substantial improvement in mental rotation skills after the intervention, with a mean difference of 23.778 (see Table 2).

Table 3
Paired differences of PSVT: R using AR learning environment

	Paired Differences					t	df	Sig. (2-Tailed)
	Mean	Std Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
PSVT: R PRE-POST	-23.778	29.457	5.384	-34.788	-12.767	-4.417	29	0.000

Table 2 provides the paired sample test results, showing that the difference in mean scores is statistically significant, with a t-value of -4.417 and a p-value of 0.000 ($p < 0.05$). The 95% confidence interval of the difference ranged from -34.788 to -12.767, which did not include zero, further confirming the significant improvement in mental rotation skills.

Tables 1 and 2 show that the AR learning environment provided to the experimental group successfully enhanced their mental rotation skills. This study extends the previous literature and suggests that AR might have a positive effect on spatial visualization (Bogomolova et al., 2020; Danakorn et al., 2019; Dickmann et al., 2021). Hedenqvist et al (2023) have been shown to enhance interactive and immersive learning experiences, leading to significant torque in students' spatial ability, whereas Bogomolova et al (2020) reported that structured interventions could be used to develop actual 3D visualization skills. The larger post-test PSVT:R scores demonstrated that the AR learning environment successfully enhanced the mental rotation ability. This enhancement is explained by the lively and interactive experience that AR allows, which provides a better understanding and memory comfort in spatial information than traditional teaching methods.

Furthermore, this study evaluated 3D development skills among students in the experimental group using both pre-test and post-test measurements with the PSVT:D. The hypotheses of this study are as follows:

H_o: There were no statistically significant differences in 3D development skills of the experimental group.

Tables 3 and 4 present the results of the paired sample statistics and paired differences for the PSVT:D pre-test and post-test scores in the experimental group, respectively, conducted in the AR Learning Environment.

Table 3
Paired samples statistics of PSVT:D using AR learning environment

	Mean	N	Std. Deviation	Std. Error Mean
PSVT: D PRE	53.967	30	17.300	3.158
PSVT: D POST	61.500	30	15.087	2.755

Table 3 shows that the mean score for PSVT:D increased from 53.967 (SD = 17.300) in the pre-test to 61.500 (SD = 15.087) in the post-test. This improvement indicated a notable enhancement in 3D developmental skills after the intervention, with a mean difference of 7.633 (see Table 4).

Table 4
Paired differences of PSVT:D using AR learning environment

	Paired Differences					t	df	Sig. (2-Tailed)
	Mean	Std Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
PSVT: D PRE- POST	-7.633	22.866	4.175	-16.172	0.905	-1.828	29	0.078

Table 4 presents the outcomes of the paired sample test, which indicate that there is a statistically significant difference in the mean scores, with a t-value of -1.828 and a p-value of 0.078 ($p > 0.05$). The 95% confidence interval for the difference ranged from -16.172 to 0.905, and because it did not include zero, it confirmed considerable improvement in 3D development skills.

These results agree with previous research, arguing that AR improves spatial ability. Serrano-Ausejo and Mårell-Olsson (2024) highlighted an immersive learning experience enabling 3D visualizations that support students' spatial abilities. Papanastasiou et al (2019) similarly emphasized the need for interventions that would provide engineers and students in technical fields with the required skills. The statistically significant increase in PSVT:D scores from pre-test to post-test indicated that students benefited from the enhanced 3D developmental skills fostered by their AR learning environment. This is partly because of the interactive nature of AR, which provides real-time participation in the learning of complex spatial concepts, leading to better comprehension and retention of information among students.

B. Mental Rotation and 3D Development Skills using Traditional Teaching Method

This study focused on the pre-test and post-test for mental rotation and 3D development skills assessments in a control group taught using typical instructional methods. The control group was administered two post-tests (PSVT:R and PSVT:D) to assess their mental rotation skills and 3D spatial skills following the intervention.

Mental rotation abilities were measured using pre-test and post-test designs that included the PSVT: R score for the control group. This study is based on the following hypotheses:

H_o: There was no significant difference in the ability of the control group to mentally rotate the 3D objects.

Tables 5 and 6 present the results of the paired sample statistics and paired differences for the PSVT:R pre-test and post-test results in the control group that received traditional teaching methods.

Table 5
Paired samples statistics of PSVT: R using traditional teaching method

	Mean	N	Std. Deviation	Std. Error Mean
PSVT: R PRE	58.889	30	23.559	4.301
PSVT: R POST	59.779	30	22.040	4.024

Table 5 shows that the mean PSVT:R score in the control group increased slightly, from 58.889 (SD = 23.559) in the pre-test to 59.779 (SD = 22.040) in the post-test. The mean difference of -0.889 (see Table 6), with standard errors of 4.301 (pre-test) and 4.024 (post-test), indicates negligible improvement in mental rotation skills after the traditional teaching intervention.

Table 6
Paired differences of PSVT: R using traditional teaching method

	Paired Differences					t	df	Sig. (2-Tailed)
	Mean	Std Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
PSVT: R PRE-POST	-0.889	31.983	5.839	-12.832	11.053	-0.152	29	0.880

Table 6 provides the paired sample test results, which reveal that the difference in mean scores is not statistically significant, with a t-value of -0.152 and a p-value of 0.880 ($p > 0.05$). The 95% confidence interval of the difference ranged from -12.832 to 11.053, which included zero, confirming the lack of significant improvement in mental rotation skills.

These results indicate that traditional teaching methods did not significantly improve the mental rotation skills of the control group at the same time point. This finding is consistent with prior research documenting the weaknesses of typical pedagogical techniques in fostering spatial thinking. Jensen and Konradsen (2018); Sorby (2009) pointed out that traditional methods fail to deliver interactive experiences, which would lead to a widespread boost in spatial skills. Conversely, innovative approaches such as AR have been shown to significantly increase these (Bacca et al., 2014; Tuker, 2018). Students who struggled with visualization did not receive sufficient support from the traditional teaching approach. Consequently, the traditional methods are unsuitable for engineering drawings.

The findings in Tables 5 and 6 demonstrate that the use of traditional teaching methods did not result in a substantial enhancement in mental rotation abilities in the control group, as indicated by the minimal increase in the PSVT:R scores. Building on these results, the subsequent analysis evaluated the effects of traditional teaching methods on the 3D development abilities of the same group.

Enhancement in the 3D development skills of students in the control group was measured using the PSVT:D as a post-test following the intervention. The hypotheses of this study are as follows:

H_o: There were no statistically significant differences in 3D development skills of the control group.

Tables 7 and 8 display the findings of the paired sample statistics and paired differences for the PSVT:D pre-test and post-test scores in the control group that underwent traditional teaching methods.

Table 7
Paired samples statistics of PSVT: D using traditional teaching method

	Mean	N	Std. Deviation	Std. Error Mean
PSVT: D PRE	38.200	30	20.486	3.740
PSVT: D POST	44.233	30	27.653	5.049

Table 7 shows that the average PSVT:D score in the control group increased from 38.200 (SD = 20.486) before the test to 44.233 (SD = 27.653) after the test. This suggests moderate advancement in 3D skill development following a conventional teaching approach, with an average difference of -6.033 (see Table 8).

Table 8
Paired differences of PSVT: D using traditional teaching method

	Paired Differences					t	df	Sig. (2-Tailed)
	Mean	Std Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
PSVT: D PRE- POST	-6.033	23.729	4.332	-14.894	2.827	-1.393	29	0.174

Table 8 provides the results of the paired sample test, which indicate that the difference in the average scores was not statistically significant, with a t-value of -1.393 and a p-value of 0.174 ($p > 0.05$). The 95% confidence interval of the difference ranged from -14.894 to 2.827, including zero, confirming the absence of significant improvement in 3D development skills.

These results are consistent with the literature and demonstrate that traditional teaching methods are not conducive to efficiently improving spatial visualization skills. Papanastasiou et al (2019); Sorby (2009) mention that traditional teaching methods might lack the interactive and engaging experience necessary to make a big change in students' spatial skills. Bacca et al (2014); Dhar et al (2021) assert that AR allows a more engaging and confident learning because these skills cannot effectively be learned by conventionally passive means. The small rise in PSVT:D scores after the intervention shows that while there may be some benefit in teaching the traditional way, this is not enough to generate adequate improvements in the development of 3D skills. This further highlights the necessity for better educational tools such as AR, which, as previously mentioned, results in better spatial visualization skills.

Conclusion

Visualization is one of the necessary skills required in engineering education; therefore, it is important for educators to know how to teach visualization and how to teach it effectively to allow students to learn this skill. To do this, educators must have the relevant competency to efficiently teach engineering drawings. The importance of drawings in engineering is that the academic success of students and the theoretical aspect of ideas are largely dependent on them. AR has been used in a variety of domains, and its exclusive advantage, especially for solving visualization problems that earlier technology could not address, has been shown in different areas such as education. The findings of this research further establish AR as a viable means of enhancing visualization skills when teaching engineering drawings. Educators can enhance students' performance and proficiency in thinking creatively by applying effective teaching strategies to engineering drawings or designs. In conclusion, AR is a powerful educational tool that has the potential to transform the learning environment into a global standard.

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