Australasian Journal of Educational Technology, 2024, 40(6).

Comparative analysis of augmented reality in an engineering drawing course: Assessing spatial visualisation and cognitive load with marker-based, markerless and Web-based approaches

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This study examined the impact of augmented reality (AR) on engineering education, focusing on spatial visualisation skills and cognitive load in an engineering drawing course. The research is based on cognitive load theory and spatial visualisation frameworks. It compares three AR methods – marker-based (MBAR), markerless (MLAR) and Web-based (WBAR) – with traditional instruction. The goal was to assess how these approaches improve spatial visualisation, measured by the Purdue Spatial Visualization Test: Rotations, and reduce cognitive load, evaluated through a validated questionnaire. The results show that the MBAR group significantly improved in spatial ability and experienced less cognitive load than the MLAR and WBAR groups. This suggests that marker-based AR is particularly effective in enhancing learning, not just in engineering but also in other fields requiring strong spatial skills. The study advocates for the broader use of AR to improve cognitive efficiency and learning outcomes.

Implications for practice or policy:

- Course designers should incorporate AR applications tailored to specific learning objectives in engineering education.
- First-year student learning outcomes can be improved by selecting AR modalities that align with course goals.
- Educators could avoid accessibility issues by prioritising inclusive design principles when implementing AR technologies.
- Assessors may need to consider the impact of AR on cognitive load when evaluating student performance.

Keywords: augmented reality (AR), engineering drawing, spatial ability, cognitive load, marker-based AR, markerless AR, Web-based AR

Introduction

The integration of augmented reality (AR) into educational settings has witnessed a growing interest, particularly in its potential to enrich and transform the landscape of engineering education (Wu et al., 2013). Despite this potential, comprehensive research examining the specific impacts of different AR modalities on critical cognitive skills in engineering education remains limited. A key challenge lies in identifying how various AR approaches influence cognitive load and spatial visualisation abilities, which are essential for understanding and interpreting complex engineering concepts (Pellegrino et al., 1984; Sorby, 2009).

Spatial visualisation is a cognitive capability pivotal in engineering disciplines, particularly in tasks such as interpreting technical drawings and visualising 3D structures. Enhancing spatial abilities can significantly improve students' performance in engineering tasks, making this a crucial area of focus (Pellegrino et al., 1984; Sorby, 2009). Cognitive load, on the other hand, refers to the mental effort required to process information and perform tasks within the cognitive system, such as memory, attention and problem-solving (Plass et al., 2010). High cognitive load can hinder learning, while optimised cognitive load can facilitate it.

Emerging trends in AR application, particularly in educational contexts, emphasise the importance of developing specialised AR tools tailored to specific learning outcomes. For example, ARPeGa, a marker-based AR application designed to teach simplified representations in mechanical drawing, was developed based on the International Organization for Standardization standards. In a pilot study with 38 mechanical engineering students, ARPeGa demonstrated significant improvements in user experience, with excellent ratings in attractiveness and good ratings in efficiency, dependability, stimulation and novelty. This suggests that AR's ability to enhance 3D model visualisation plays a crucial role in improving user experiences and comprehension of complex concepts (Wardhani, 2024).

Similarly, in industrialised construction, AR is recognised for its potential to improve product quality by addressing quality issues in complex assembly projects. A novel approach involving projection-based AR in construction manufacturing facilities allows for precise projection alignment using vision-based techniques. Experimental studies have shown that this method can maintain accuracy within factory tolerance levels, even in varying environmental conditions. This trend highlights AR's expanding role in not only educational settings but also in practical, industry-specific applications (Ahn et al., 2019).

In light of these emerging trends, this study explored the use of AR applications within an engineering drawing (ED) course, aiming to thoroughly examine their impact on students’ cognitive load and spatial visualisation abilities. The rationale for including three distinct AR modalities – marker-based AR (MBAR), markerless AR (MLAR) and Web-based AR (WBAR) – was to compare their effectiveness in a controlled manner and understand the specific advantages and limitations each approach offers. MBAR uses physical markers to overlay digital content, aiding in precise placement and interaction with virtual objects. MLAR, on the other hand, does not require physical markers, offering more flexibility and a seamless user experience. WBAR allows for easy access via web browsers without the need for specialised hardware or software, making it more accessible and scalable.

In a comprehensive exploration, we designed a systematic investigation employing four distinct groups – three experimental groups (EGs) and one control group (CG) – each comprising 35 undergraduate students. The EGs engaged with diverse AR applications, namely MBAR, MLAR and WBAR, while the CG adhered to the traditional method of teaching. This study is unique in its comparative analysis of multiple AR modalities, providing a nuanced understanding of their specific impacts on cognitive load and spatial visualisation. By evaluating these distinct AR approaches, this research aimed to uncover subtle differences and offer insights into the most effective methods for enhancing engineering education. This study explored the effectiveness of various AR modalities in engineering education; it strengthens the existing body of knowledge through the use of rigorous quantitative assessments. Specifically, the study utilised the Purdue Spatial Visualization Test: Rotations (PSVT-R) to evaluate spatial abilities and employed a detailed cognitive load questionnaire (Hwang et al., 2016; Yoon, 2011). These robust methods ensure that the findings are both reliable and relevant, contributing valuable insights to the ongoing discourse on educational technologies. The study addressed the research following questions:

- Are there any significant differences in the spatial ability of students using different types of AR applications (MBAR, MLAR and WBAR) and those in the control group?
- Are there any significant differences in the cognitive load experienced by students using different types of AR applications (MBAR, MLAR and WBAR) and those in the control group?
- Are there any significant differences in intrinsic and extraneous cognitive load between students using different types of AR applications (MBAR, MLAR and WBAR) and those in the control group?

Related work

AR

The fusion of AR with educational methodologies represents an ideal shift in contemporary pedagogical practices (K. Lee, 2012). AR, characterised by the overlay of digital information onto the physical world, has gained prominence across diverse disciplines, demonstrating potential avenues for enhancing learning experiences (R. Azuma et al., 2001; R. T. Azuma, 1997). Within the domain of engineering education, the integration of AR has emerged as a compelling area of exploration, prompting scholars and educators to investigate its multifaceted impact on student engagement, comprehension and skill development. AR applications are of three different types: MBAR, MLAR and WBAR (Genc et al., 2002; Gherghina et al., 2013; Qiao et al., 2019). In MBAR, digital content is superimposed onto physical objects using visual markers as reference points (Seo et al., 2011). Studies exploring MBAR in education have highlighted its potential to enhance student engagement, promote interactive learning and facilitate a deeper understanding of complex concepts (Fleck et al., 2015; Tiwari et al., 2024). The visual alignment between physical objects and digital overlays in MBAR offers seamless integration of virtual information into the real-world environment (Liu & Tanaka, 2021). MLAR represents a departure from MBAR approaches by leveraging advanced computer vision techniques to track and augment the physical environment without the need for predefined markers (Genc et al., 2002). The MLAR application offers increased flexibility and spontaneity in AR experiences, as it does not rely on specific visual cues. Studies suggest that MLAR applications contribute to improved immersion and a sense of authenticity in learning experiences, fostering a dynamic and responsive educational environment (B. Lee & Chun, 2010). WBAR introduces a layer of interactivity by integrating AR experiences directly into web browsers (Qiao et al., 2019). This approach eliminates the need for specialised applications, enhancing accessibility and ease of deployment (Qiao et al., 2018). In educational settings, WBAR has been recognised for its versatility, enabling learners to access augmented content seamlessly through web browsers on various devices. This approach aligns with the evolving landscape of online and remote learning, providing educators with a scalable and user-friendly means to incorporate AR into their instructional strategies (Chen et al., 2011). However, there are studies that underscored specific limitations associated with these different versions of AR applications. In the realm of MBAR, technical issues such as marker tracking challenges and the necessity for substantial device compatibility have been identified (Ashiwini et al., 2020; Herout et al., 2012; Pombo & Marques, 2017; Rabbi & Ullah, 2013). Challenges associated with WBAR included potential latency issues and reliance on stable Internet connections (Qiao et al., 2019). Moreover, MLAR exhibited difficulties in maintaining accurate spatial overlays, leading to potential misinterpretations (Brito & Stoyanova, 2018; J. C. Cheng et al., 2017; Lima et al., 2017; Ufkes & Fiala, 2013).

Despite these challenges, the integration of AR in educational settings has been shown to significantly enhance the learning experience by visualising complex subjects. For instance, a study using AR tools such as ArloonGeometry and Geometry AR in teaching geometry to students in Grades 7–9 revealed that these tools not only improved academic success but also reduced fear and anxiety. They created positive emotional interactions that foster better memorisation and creativity in solving geometric problems (Rashevska et al., 2020). Another research explored the development of a mobile AR application for projection drawing tasks in technical disciplines, highlighting the process from creating virtual models to developing and testing the application using the Unity SE platform (Kanivets et al., 2020). This AR application was found to be effective for both independent student work and classroom activities in higher education. Similarly, the use of AR in studying simple electric circuits demonstrated the feasibility and benefits of developing mobile AR apps for educational purposes (Kanivets et al., 2022). The application allowed students to visualise and interact with electronic models, thereby enhancing their understanding and engagement. Finally, research on a mobile AR application for radiochemistry and radioecology showcased how 3D visualisations of complex concepts similar to radionuclides, radioisotopes and nuclear reactions could significantly aid in comprehension and retention (Midak et al., 2021). This study emphasised the importance of equipping future educators with AR technology skills to improve teaching methodologies. Collectively, these studies underscore the transformative potential of AR in making abstract and complex educational content more accessible and engaging. They also highlighted concerns regarding the learning curve and technical glitches, impacting the overall user experience for individuals becoming familiar with AR interfaces (Pooja et al., 2020).

Spatial ability in an ED course

Spatial ability is crucial in the context of ED courses as it empowers students to conceptualise and comprehend complex 3D objects (Marunić & Glazar, 2014; Pellegrino et al., 1984). Proficiency in spatial skills is demonstrated by the ability to mentally visualise the various components of an object and their interrelationships, a prerequisite for accurately rendering it (Marunić & Glazar, 2012). Additionally, students must possess the capability to mentally manipulate and rotate objects to generate diverse perspectives. Empirical evidence indicates a positive correlation between adept spatial skills and enhanced performance in engineering drawing courses (Akkuş & Arslan, 2022). A study conducted by Marunić and Glazar (2014) illustrated that students with elevated spatial skills consistently outperformed their counterparts with lower spatial abilities in ED courses.

Traditionally, pedagogical approaches in ED courses have relied on hands-on activities, physical models and conventional drawing tools to cultivate spatial skills (Wang et al., 2019). While effective, these methods present challenges related to scalability and adaptability to varied learning styles. The introduction of computer-aided design (CAD) software has significantly transformed the landscape of engineering drawing education. CAD tools, such as AutoCAD and SolidWorks, furnish a digital platform for the creation and manipulation of 3D models (Maguire, 1998; Shih, 2013). Research suggests that CAD contributes to heightened spatial visualisation skills and facilitates real-time feedback (Marunić & Glazar, 2014). Nonetheless, challenges associated with a steep learning curve for novices and the potential for excessive reliance on software-generated solutions pose limitations, potentially undermining the development of hand-drawing skills (Salzman et al., 1989).

The integration of 3D printing into ED courses represents a pivotal advancement, allowing students to materialise their designs physically (Zaman et al., 2020). This hands-on approach augments spatial understanding by establishing a tangible connection between digital models and physical objects (Mo & Tang, 2017). However, challenges include the cost implications associated with 3D printers and materials, along with the time-intensive nature of printing intricate models (Schelly et al., 2015). Furthermore, the infusion of gamification elements, such as spatial puzzles and interactive simulations, introduces a dynamic and enjoyable dimension to the learning experience (Schwering et al., 2014). These technological interventions serve to democratise spatial learning, making it more accessible to a broader spectrum of learners (Sudarmilah & Arbain, 2019). Nonetheless, potential drawbacks include the risk of distractions and the imperative for meticulous instructional design alignment with educational objectives (Tóth et al., 2021). The synthesis of these diverse methodologies offers a nuanced perspective on the multifaceted landscape of spatial skills development in engineering drawing education.

AR and spatial ability

AR emerges as a tool capable of fostering interactive learning experiences, specifically tailored to augment students' spatial skills (Carbonell Carrera & Bermejo Asensio, 2017). An expanding body of research indicates a positive correlation between the use of AR and enhanced spatial ability among students. For instance, a study conducted by Majgaard et al. (2017) demonstrated that students utilising an AR application for solar system education outperformed their counterparts employing traditional learning methods in spatial ability assessments. Similarly, Jain et al. (2017) observed enhanced spatial ability in students engaging with an AR application for human anatomy compared to those employing conventional learning techniques. These AR applications facilitated a 3D representation of complex objects, aiding students in comprehending the spatial relationships intrinsic to these subjects (Kru¨ger et al., 2022; Krüger et al., 2022). By employing AR, educators can craft simulations and interactive modules, enhancing students' understanding of spatial concepts in an enjoyable and engaging manner (Duncan-Vaidya & Stevenson, 2021). The integration of AR into pedagogical practices aligns with a constructivist approach, affording teachers the ability to introduce tangible and interactive learning experiences into the classroom, thereby enabling students to interact with and manipulate educational objects (Dünser et al., 2006; Kaufmann et al., 2005).

Impact of AR on cognitive load

Cognitive load refers to the mental effort and resources required to perform a task or complete a cognitive activity. This phenomenon can be quantified through diverse approaches, including subjective self-reports, behavioral performance, physiological responses, and neuroimaging techniques (Hart &

Staveland, 1988). The importance of considering cognitive load during the process of teaching is grounded in cognitive load theory and the underlying assumption that the human cognitive architecture comprises a sensory register, a working memory with limited capacity and a long-term memory with unlimited storage capacity (Sweller, 1988). Cognitive load theory identifies two types of cognitive load: intrinsic and extraneous cognitive load. Intrinsic cognitive load is associated with the complexity of the material itself; extraneous cognitive load relates to how the material is presented (Klepsch & Seufert, 2020).

The integration of AR in education has gained attention due to its potential to influence cognitive load. The association between AR and the cognitive theory of multimedia learning can be attributed to AR's capacity to concurrently depict verbal and visual information (Mayer, 2002; Baumeister et al., 2017). Therefore, the inclusion of AR in an educational environment may lead to a decrease or sustained reduction in extraneous cognitive load, leading to improved learning outcomes and task execution (Bressler & Bodzin, 2013; Goff et al., 2018; Sommerauer & Müller, 2014). However, the potential for cognitive overload is a significant concern that must be taken into account when utilising AR for educational purposes (Akçayır & Akçayır, 2017; K.-H. Cheng & Tsai, 2013; Wu et al., 2013). To mitigate this, it is crucial to design AR content that is intuitive and aligns closely with educational goals. Effective strategies include simplifying the interface, ensuring that the AR content complements rather than complicates the learning material, and providing adequate training for both educators and students on how to use AR tools effectively (Akçayır & Akçayır, 2017). It is important to note that not all studies have reported positive effects; some research indicates that AR can occasionally lead to cognitive overload, particularly when the interface is overly complex or the content is not well-integrated with the learning objectives (Elford et al., 2022; Lai et al., 2019).

In this context, studies by Pellegrino et al. (1984) and Sorby (2009) underscored the importance of spatial ability in engineering disciplines, highlighting its role in problem-solving and technical comprehension. Cognitive load theory, as outlined by Sweller (2010), distinguishes between intrinsic, extraneous and germane cognitive loads, which are relevant to AR-based learning. The use of AR can affect these cognitive loads differently; it can reduce extraneous cognitive load by providing clear and interactive visualisations but may increase intrinsic cognitive load if the content is inherently complex. Research by Di Serio et al. (2013) and Bacca et al. (2014) has suggested AR's ability to enhance learning through immersive environments, although noting challenges such as increased extraneous load. Comparative studies (Akçayır & Akçayır, 2017) on AR modalities – MBAR, MLAR and WBAR – reveal varying effectiveness and implementation contexts. Wu et al. (2013) has advocated for AR's transformative potential in bridging theoretical knowledge and practical application in engineering education. This study addresses these gaps by systematically evaluating MBAR, MLAR and WBAR impacts on cognitive load and spatial visualisation, using tools like the PSVT-R and cognitive load questionnaires (Hwang et al., 2016), aiming to offer insights for effective AR integration in engineering drawing curricula.

Experimental setup

Study design and data sample

This study used a true experimental design. A total of 140 first-year college students aged 19–22 years were randomly allotted to four different groups. Each group consisted of 35 students, comprising one CG and three EGs (EG1, EG2 and EG3). We used the random sample approach to select students for the experiment. Table 1 shows the demographic information of the students who took part in the study. The difference among the three EGs is in their adoption of different AR approaches. Specifically, EG1 used the MBAR approach, EG2 employed the MLAR approach and EG3 utilised the WBAR approach. This study was ethically approved by the Indian Institute of Technology, Kharagpur.

Table 1
Demographic details

Measure	Category	Number	Percentage (%)
Gender	Female	44	31.42
	Male	96	68.57
	Total	140	
Age (years)	19	43	30.71
	20	69	49.28
	Above 20	28	20.00
	Total	140	
Department (undergraduate)	Computer Science Engineering	29	20.71
	Mechanical Engineering	19	13.57
	Electronics Engineering	27	19.28
	Civil Engineering	11	7.85
	Electrical Engineering	26	18.57
	Other	28	20.00
	Total	140	

AR application development

We developed the AR application using the Unity SE platform and designed in three different types – MBAR, MLAR and WBAR (see Figures 1, 2 and 3). Each type incorporates essential concepts such as the projection of planes, lines, solids, cross-sections of solids and orthographic projection. The WBAR application is accessible via a specified URL. Before using the application, we instructed students on its basic features to ensure ease of use, allowing them to focus on learning without significant functional difficulties. We then encouraged students to explore the content and actively engage with the application's features.

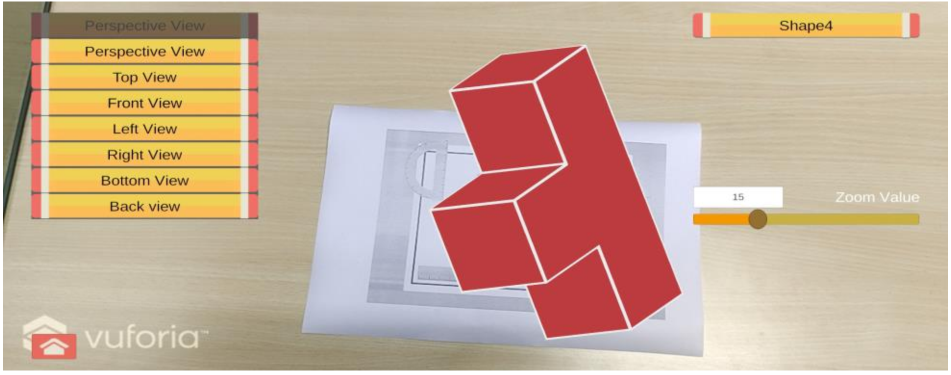

Figure 1. Snapshot of MBAR application

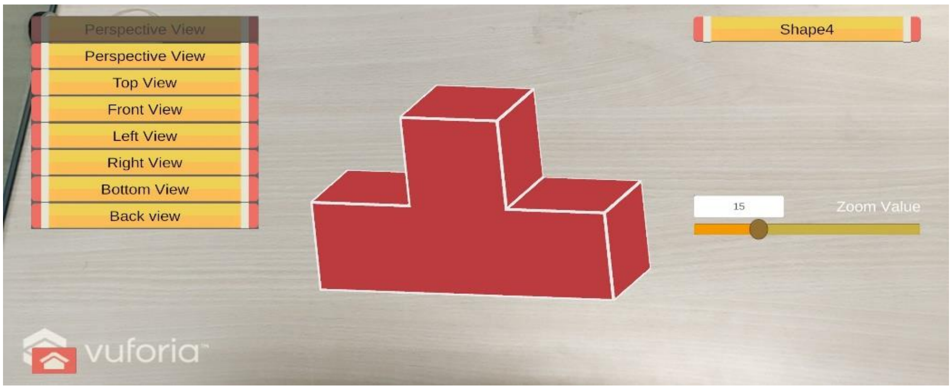

Figure 2. Snapshot of MLAR application

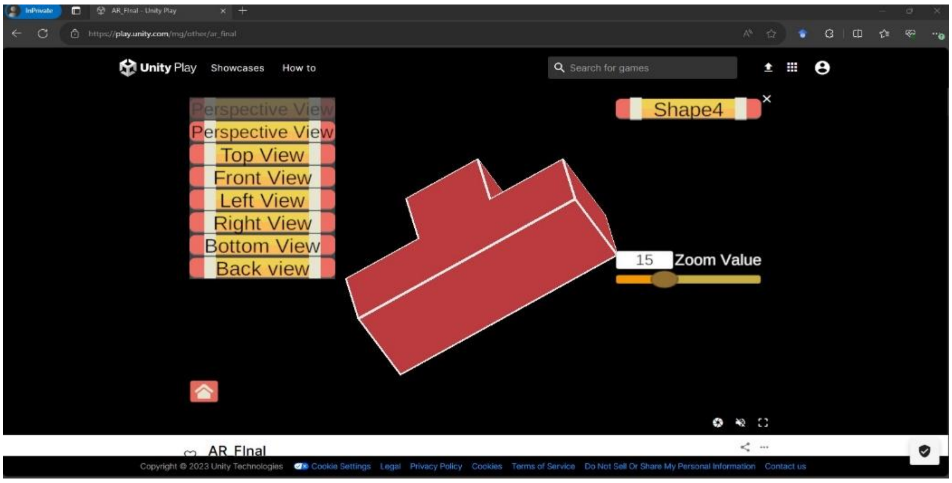

Figure 3. Snapshot of WBAR application

Instruments

PSVT-R

The PSVT-R has emerged as a widely acknowledged quantitative measure for assessing spatial aptitude (Yoon, 2011). This instrument, characterised by its focus on mental rotation tasks, provides a standardised means to evaluate individuals' spatial abilities. Given its relevance to the cognitive aspects crucial for success in engineering pursuits, the PSVT-R serves as a relevant metric for discerning the impact of AR applications on spatial visualisation skills among engineering students. The test consists of 30 multiple-choice questions requiring participants to present a 3D object and several possible rotated versions of that object. We randomly selected 15 test items for the pre-test and the remaining 15 for the post-test to evaluate the effect of different types of AR applications on the spatial ability of each group's participants. Figure 4 shows an example of one of the questions, similar to those which were included in the pre-test and the post-test. They were awarded one mark for each correct answer, while no marks were given for incorrect answers. The Cronbach's alpha for PSVT-R was 0.84, which is acceptable (Barrett, 2001).

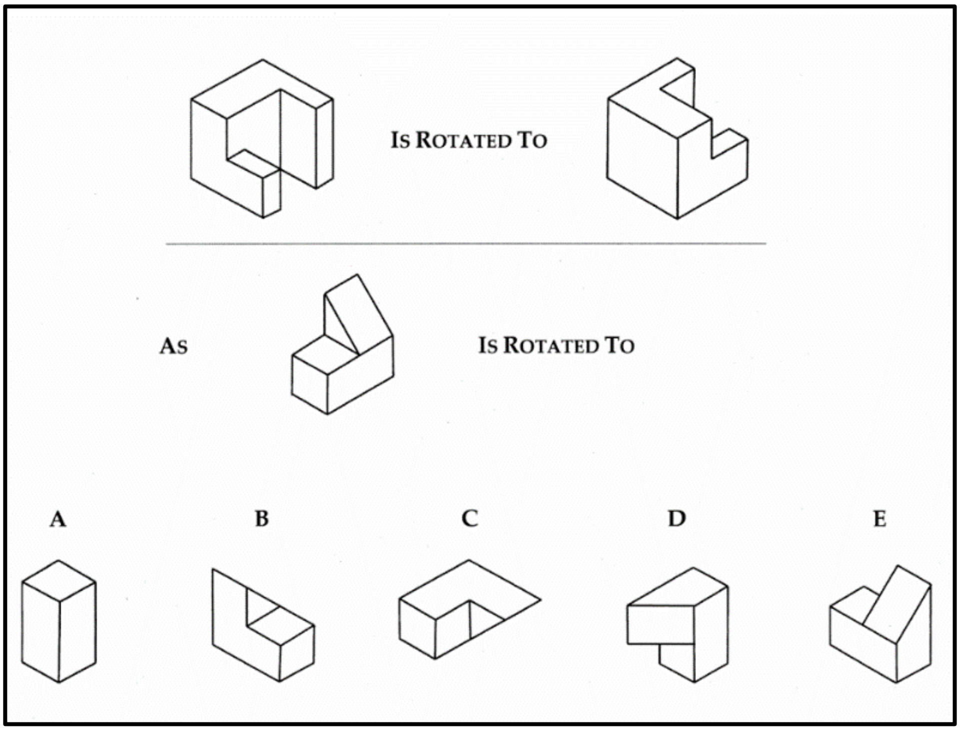

Figure 4. Sample image of questions included in the pre-test and post-test

Cognitive load

We used a 5-point Likert scale questionnaire developed by Hwang et al. (2016) to evaluate the effect of AR applications on the cognitive load of participants. It has two dimensions: mental effort and mental load. There were a total of eight items in the questionnaire (see Appendix A). The Cronbach's alpha coefficients for the mental load and mental effort dimensions were 0.86 and 0.85, respectively, which are acceptable (Barrett, 2001).

Experimental design

Figure 5 illustrates the experimental design employed in our study. Initially, all groups underwent a pre-test using the PSVT-R. Subsequently, participants in the EGs were instructed to utilise their respective versions of the AR app (MBAR, MLAR and WBAR) to study ED for 30 minutes, while the CG used the traditional content to study ED during the same time frame. The traditional content includes YouTube links and slides for learning similar content to that provided in the AR application. Following the study period, all groups completed a post-test using the PSVT-R test and cognitive load questionnaire.

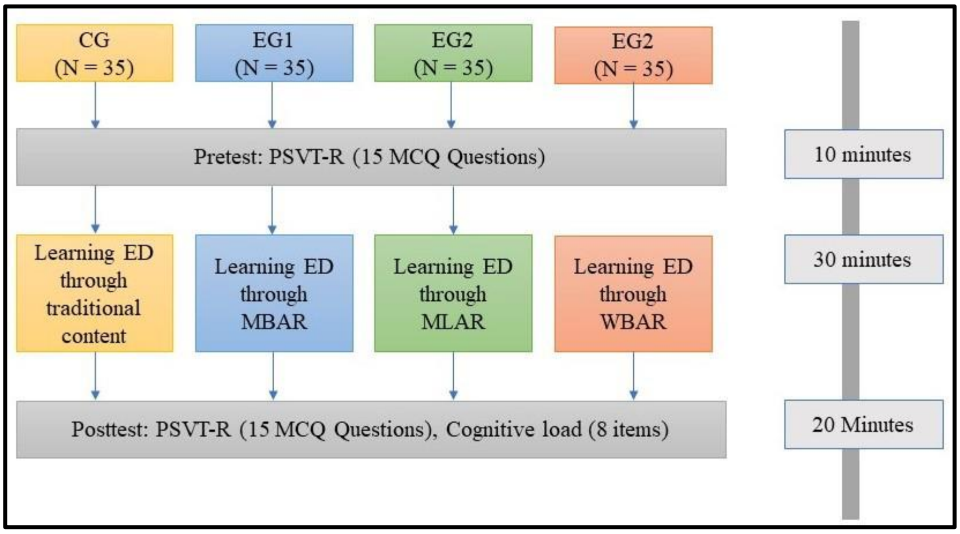

Figure 5. Research methodology

Data analysis

We conducted an analysis of the collected data using both descriptive statistics and inferential statistics. We used multivariate analysis of covariance (MANOVA) for our study. Skewness and kurtosis were calculated to assess the normality of the data. The skewness and kurtosis values of all the variables are within the acceptable limits of /3/ and /10/, respectively (Kline, 2023). The statistical analyses were performed using the Statistical Package for the Social Sciences, specifically version 21.

Results

Spatial ability

Table 2 shows the results of the PSVT-R test for the CG and the three EGs. In the PSVT-R pre-test, the EG1 scored 7.94 with a standard deviation of 1.99, the EG2 group scored 8.14 with 2.08, the EG3 scored 7.80 with 1.86 and the CG scored 8.37 with 1.95. The results indicated no significant differences in performance between the four groups in the pre-test of the PSVT-R test ($F = 0.55$, $p > 0.05$). In the PSVT-R post-test, the EG1 scored 12.80 with a standard deviation of 1.79, the EG2 scored 11.57 with 1.89, the EG3 scored 13.31 with 1.40 and the CG scored 10.82 with 1.77. The results indicated significant differences in performance between the four groups in the post-test of the PSVT-R test ($F = 15.04$, $p < 0.05$). The EG1 had a mean achievement gain score of 4.85 with a standard deviation of 2.75, the EG2 had 3.42 with 2.66, the EG3 had 5.51 with 2.40 and the CG had 2.45 with 2.72. The PSVT-R gain scores of the four groups differed significantly (*F* = 9.56, *p* < 0.05). The EG3, which scored the lowest pre-test, scored the highest post-test.

Table 2
MANOVA results of pre-and post-test of PSVT-R

Test	Group	Mean	SD	F value	*p*	Post-hoc, effect size (ES)
Pre	EG1	7.94	1.99	0.55	0.64	
	EG2	8.14	2.08			
	EG3	7.80	1.86			
	CG	8.37	1.95			
Post	EG1	12.80	1.79	15.04*	0.001	EG1 > EG2*, ES(d) = 0.67 EG1 > CG*, ES(d) = 1.11
	EG2	11.57	1.89			EG2 > CG, ES(d) = 0.40
	EG3	13.31	1.40			EG3 > EG2*, ES(d) = 1.04 EG3 > EG1, ES(d) = 0.31 EG3 > CG*, ES(d) = 1.56
	CG	10.82	1.77			
Gain	EG1	4.85	2.75	9.56*	0.002	EG1 > EG2*, ES(d) = 0.52 EG1 > CG*, ES(d) = 0.87
	EG2	3.42	2.66			EG2 > CG, ES(d) = 0.36
	EG3	5.51	2.40			EG3 > EG2*, ES(d) = 0.82 EG3 > EG1, ES(d) = 0.25 EG3 > CG*, ES(d) = 1.19
	CG	2.45	2.72			

**p* < .05.

Cognitive load

Table 3 shows cognitive load survey results from experimental and CG s. The results showed that cognitive load differed among groups (*F* = 48.18, *p* < 0.05). We found that EG1 had the lowest level of cognitive load among all the groups.

Table 3
One-way ANOVA results of cognitive load survey

Group	Mean	SD	F value	*p*	Post-hoc, effect size (ES)
EG1	1.28	0.29	48.18*	0.001	EG1 > EG3*, ES(d) = 2.56
EG2	2.08	0.35			EG2 > EG3, ES(d) = 0.12 EG2> EG1*, ES(d) = 2.48 EG2 > CG*, ES(d) = 0.34
EG3	2.04	0.28			EG3 > CG*, ES(d) = 0.25
CG	1.96	0.34			CG > EG1*, ES(d) = 2.15

**p* < .05.

Table 4 presents the mean and standard deviations of cognitive load measures across four groups, examined through MANOVA to assess the impact of AR-based learning approaches on students' mental load and mental effort. The MANOVA results show significant differences in both mental load and mental effort among the groups (mental load: *F* = 39.34, *p* < 0.05; mental effort: *F* = 19.86, *p* < 0.05).

The analysis indicates that the different AR-based approaches result in varying levels of mental load. Specifically, EG2 demonstrated the highest mental load (M = 2.06, SD = 0.36), significantly greater than EG1 (M = 1.23, SD = 0.28) and EG3 (M = 1.98, SD = 0.41), with effect sizes of ES(d) = 2.57 and ES(d) = 2.13, respectively. This suggests that the AR approach used in EG2 leads to a higher intrinsic cognitive load, potentially due to the complexity or intensity of the material presented. In contrast, CG (M = 1.98, SD = 0.38) showed similar mental load levels to EG3, but CG had a significantly lower mental load compared to EG1 (ES(d) = 2.24), indicating that CG might have been less complex or better integrated with learning objectives. The results suggest that EG2 may be more demanding in terms of intrinsic cognitive load. The results for mental effort reveal that EG2 (M = 2.11, SD = 0.47) required significantly more mental effort compared to EG1 (M = 1.37, SD = 0.39), with an effect size of ES(d) = 1.84. This higher mental effort is consistent with the higher mental load reported for EG2, reflecting increased cognitive demands. EG2 also had greater mental effort compared to EG3 (M = 2.10, SD = 0.49) and CG (M = 1.92, SD = 0.47), with effect sizes of ES(d) = 0.02 and ES(d) = 0.40, respectively. This indicates that the AR approach in EG2 might be more complex or less intuitive, leading to higher extraneous cognitive load and mental effort. On the other hand, EG3 required more mental effort than CG (ES(d) = 0.37), which could suggest that EG3 involves more complex or less effectively designed AR elements compared to the CG. Overall, these findings highlight that different AR-based learning approaches affect both intrinsic and extraneous cognitive loads. EG2 tends to increase both intrinsic and extraneous loads, while EG1 and CG demonstrate comparatively lower cognitive demands, indicating potential differences in the effectiveness and integration of AR content across the groups.

Table 4
MANOVA results of mental load and mental effort

Dimensions	Group	Mean	SD	F-value	*p*	Post-hoc, effect Size (ES)
Mental load	EG1	1.23	0.28	39.34*	0.001	
	EG2	2.06	0.36			EG2 > EG1*, ES(d) = 2.57 EG2 > EG3, ES(d) = 0.20 EG2 > CG, ES(d) = 0.21
	EG3	1.98	0.41			EG3 > EG1*, ES(d) = 2.13
	CG	1.98	0.38			CG > EG1*, ES(d)= 2.24 CG > EG3, ES(d)= 0.00
Mental effort	EG1	1.37	0.39	19.86*	0.003	
	EG2	2.11	0.47			EG2> EG1*, ES(d) = 1.84 EG2 > EG3, ES(d) = 0.02 EG2 > CG, ES(d) = 0.40
	EG3	2.10	0.49			EG3 > EG1*, ES(d) = 1.64 EG3 > CG, ES(d) = 0.37
	CG	1.92	0.47			CG > EG1*, ES(d) = 1.27

$^*p < .05$.

Discussion

This study aimed to assess the effectiveness of AR in an ED course through a comparative analysis of MBAR, MLAR and WBAR approaches. The research comprised three different EGs (EG1, EG2 and EG3) that utilised these AR applications to study ED, while the CG employed conventional learning approaches. Subsequently, an assessment was conducted to determine the impact of the AR approaches on the spatial ability and cognitive load of students.

Key findings from the study indicate that all three AR approaches (MBAR, MLAR and WBAR) positively impacted spatial ability compared to the CG. This confirms the first research question, demonstrating that AR technology can enhance students' spatial skills, crucial for understanding technical drawings. These results align with studies emphasising AR's potential in improving spatial abilities (Akçayır & Akçayır, 2017; Santos et al., 2013). However, a closer analysis reveals differences in effectiveness among the AR approaches. MBAR and WBAR were found to be more effective in enhancing spatial skills compared to MLAR. This disparity might be attributed to the absence of predetermined markers in MLAR, which can result in restricted tracking precision and affect 3D model visualisation. The findings suggest that although MLAR offers flexibility and ease of use, these advantages may come at the cost of spatial clarity and accuracy. This trade-off highlights the importance of considering the technical limitations of AR modalities in educational contexts. The enhanced performance of MBAR and WBAR may be due to their more stable and reliable visual cues, which provide students with clearer and more consistent spatial information. These insights align with research that has compared various AR technologies in the context of spatial ability enhancement (Batch et al., 2023; K.-H. Cheng & Tsai, 2013).

The second and third research questions investigated how different AR approaches – MBAR, MLAR and WBAR – affect students' cognitive load. The results revealed that all three AR methods significantly reduce cognitive load compared to traditional engineering drawing teaching methods, indicating that AR technology can effectively manage both intrinsic and extraneous cognitive load associated with complex spatial tasks (İbili, 2009). The MBAR approach was particularly effective in reducing cognitive load, primarily due to its use of physical markers to trigger AR content, which provides clear spatial cues and integrates virtual objects with the physical environment. This integration simplifies spatial tasks and reduces intrinsic cognitive load by offering a clear reference frame, while also minimising extraneous cognitive load through an intuitive interface that reduces cognitive distractions. Although these results align with findings on the effectiveness of AR in managing cognitive load (Buchner et al., 2022; Keller et al., 2021), it is important to critically evaluate the reliance on physical markers, which may limit the flexibility and broader applicability of MBAR in various learning environments.

MLAR and WBAR also contributed to reductions in cognitive load, though their effectiveness was variable. MLAR, while advantageous in its elimination of physical markers, sometimes lacked the same level of spatial clarity and stability, potentially impacting its ability to manage intrinsic load effectively. This suggests that the flexibility of MLAR may introduce variability that could hinder consistent cognitive load reduction, particularly in tasks requiring precise spatial manipulation. WBAR provided easy access and scalability but faced challenges such as latency and lower interaction quality, which could affect its effectiveness in reducing extraneous load. These findings underscore the need for a nuanced understanding of how different AR modalities interact with cognitive processes, as each has unique strengths and weaknesses that can influence learning outcomes.

Overall, these findings underscore that although all AR approaches can alleviate cognitive load, the MBAR method is particularly effective in reducing both intrinsic and extraneous cognitive load, enhancing students' ability to understand and interact with complex spatial concepts (Lim et al., 2019).

Conclusions

This study contributes to the growing body of literature on the effectiveness of AR in education, specifically within the field of ED. The findings suggest that incorporating AR technology, whether MBAR, MLAR or WBAR, can improve students' spatial ability and reduce cognitive load. The MBAR approach demonstrated advantages in terms of lower cognitive load, but all three approaches showed positive effects on spatial ability. These results highlight the potential of AR as a valuable tool for enhancing learning experiences in ED courses. Moreover, the cognitive load surveys provided valuable information on the mental demands, and mental effort experienced by participants. The results indicated that the AR groups, particularly EG1 and EG2, experienced lower cognitive loads compared to the CG, indicating that AR can reduce mental load and improve learning efficiency. Through detailed analysis of the outcomes, this research contributes empirical insights that relate to both students and subject matter experts, offering guidance on the potential benefits and considerations in the integration of AR technologies into ED curricula. In doing so, it adds to the ever-evolving discourse on the transformative potential of AR in education, paving the way for more informed decisions and enriched learning experiences in the field of engineering.

Limitations and future work

This research aimed to comprehensively explore the impact of AR technology on learning outcomes in an ED course. This study has several limitations that should be acknowledged. Firstly, cognitive load was measured using an 8-item questionnaire, which, despite having acceptable internal consistency, may not fully capture all dimensions of cognitive load, such as intrinsic, extraneous and germane load, potentially affecting the comprehensiveness of the results. The sample consisted of 105 undergraduate students from a single institution, limiting the generalisability of the findings to other educational settings or institutions. This homogeneous sample may not reflect diverse learning environments or account for institutional factors that influence learning outcomes, such as differences in curriculum, teaching methods or access to technology. The study also did not account for all potential interaction effects between AR modality and individual learning differences, which could introduce variability in the outcomes. Variables such as prior experience with AR, spatial ability and individual preferences for different learning modalities were not controlled or measured, potentially contributing to unexplained variance in the results. Moreover, the absence of qualitative insights into students' experiences with AR modalities restricts the understanding of user perceptions and specific strengths or weaknesses of each technology. Qualitative feedback could have illuminated how different AR approaches influence engagement, motivation and perceived ease of use, providing a more comprehensive view of the student experience. Future research should address these limitations by employing more comprehensive cognitive load measurement tools, for example, NASA Task Load Index, utilising larger and more diverse sample populations and incorporating longitudinal designs to assess long-term effects. Additionally, including qualitative methods to explore students' experiences and expanding the comparative analysis to consider factors such as ease of use and engagement will provide a more nuanced understanding of the effectiveness of AR technologies in enhancing engineering education.

Author contributions

Author 1: Conceptualisation, Investigation, Data curation, Formal analysis, Writing – original draft; **Author 2**: Conceptualisation, Investigation, Data Curation, Formal analysis, Writing – review and editing.

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Please cite as: Tiwari, A. S. & Bhagat, K. K. (2024). Comparative analysis of augmented reality in an engineering drawing course: Assessing spatial visualisation and cognitive load with marker-based, markerless and Web-based approaches. *Australasian Journal of Educational Technology*, *40*(6), 19–36. https://doi.org/10.14742/ajet.9217

Appendix A

Cognitive load (5-point scale – *strongly disagree* 1 to *strongly agree* 5)

Mental load

1. The learning content in this learning activity was difficult for me.
2. I had to put a lot of effort into answering the questions in this learning activity.
3. It was troublesome for me to answer the questions in this learning activity.
4. I felt frustrated answering the questions in this learning activity.
5. I did not have enough time to answer the questions in this learning activity.

Mental effort

6. During the learning activity, the way of instruction or learning content presentation caused me a lot of mental effort.
7. I need to put lots of effort into completing the learning tasks or achieving the learning objectives in this learning activity.
8. The instructional way in the learning activity was difficult to follow and understand.