

ORIGINAL RESEARCH ARTICLE

Does utilising augmented reality in learning process improve student's cognitive processing? A cognitive absorption approach

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Augmented reality (AR) integration in learning aims to improve overall educational experiences through multiple pathways, with cognitive processing enhancement serving as a fundamental mechanism. Whilst AR's benefits encompass motivation, engagement and satisfaction, understanding how AR influences cognitive processing provides crucial insights into the underlying mechanisms that drive these broader improvements. Despite broad recognition of this goal, it remains underexplored. Drawing on cognitive absorption theory, this study examines how key cognitive absorption factors influence cognitive processing benefits. Data were collected from 184 university students and analysed using partial least square-structural equation modelling and importance-performance map analysis (IPMA). Findings reveal that enjoyment, control and curiosity significantly influence perceived usefulness (PU) ($R^2 = 62.4\%$) and ease of use ($R^2 = 65.4\%$). These factors, in turn, mediate immersive experiences ($R^2 = 63.7\%$), which significantly affect cognitive processing benefits ($R^2 = 55.3\%$). The results suggest that within AR-based learning, traditional technology acceptance models should be reconsidered. Notably, whilst perceived ease of use and enjoyment are important (as shown by IPMA), they do not significantly impact PU. Additionally, multi-group analysis indicates that AR-supported learning results in consistent cognitive processing outcomes for students from both natural and social sciences, suggesting AR's broad applicability across academic disciplines.

Keywords: augmented reality; cognitive absorption theory; technology acceptance model; cognitive processing benefits; immersion AR

Introduction

Augmented reality (AR) has emerged as a powerful educational tool, offering an interactive and engaging learning experience that enhances focus, comprehension and memory. Traditional teaching methods often fail to captivate learners, whereas AR integrates digital elements into real-world contexts, creating rich opportunities for immersive learning (Aldeeb et al., 2024; Gill et al., 2025). Cognitive processing enhancement serves as a foundational mechanism that underlies many of these benefits. Its adoption in higher education marks a transformative shift in pedagogy,

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emphasising the need to explore how AR fosters cognitive processing benefits amongst university students.

Recent studies confirm AR's positive impact on learning outcomes, emphasising its cognitive advantages (Aldeeb et al., 2024; Alkhabra et al., 2023; Gill et al., 2025; Khodabandeh, 2023; Radu et al., 2023; Singh & Ahmad, 2024). These studies draw from diverse theoretical foundations such as cognitive load theory (Kairu, 2021), affordance theory (Laine et al., 2023), uses and gratification theory (Baabdullah et al., 2022) and cognitive absorption theory (Guerra-Tamez, 2023). For example, Gill et al. (2025) observed increased motivation and attention amongst students in AR-supported environments, whilst others found AR encourages critical thinking and problem-solving skills (Aldeeb et al., 2024).

Moreover, AR reduces cognitive load and enhances understanding, especially in abstract subjects like physics and mathematics (Thees et al., 2020). Studies show that AR enables learners to visualise and interact with complex concepts, improving memory retention and knowledge transfer (Radu et al., 2023). AR's capacity for personalised learning – allowing self-paced engagement – further supports cognitive development and learner satisfaction (Aldeeb et al., 2024).

This study advances cognitive absorption theory (Agarwal & Karahanna, 2000) by empirically testing how cognitive factors influence AR adoption and its cognitive outcomes in education. Whilst prior research focused on cognitive absorption's link to technology use, this study introduces technology acceptance as a mediating variable between cognitive engagement and immersion (IM), which subsequently leads to cognitive gains. This approach addresses a gap in understanding how immersive experiences foster cognitive outcomes. By examining cognitive processing benefits through the lens of cognitive absorption theory, this study provides insights into the fundamental mechanisms through which AR achieves its broader educational goals.

Practically, the findings offer guidance for educators and developers in designing AR tools that are not only functional and user-friendly but also deeply engaging on a cognitive level.

This paper proceeds as follows: Section 2 outlines the theoretical background; Section 3 details the research model and hypotheses; Section 4 presents the methodology; Section 5 covers data analysis and results; Section 6 discusses findings and conclusions; and Section 7 addresses limitations and future research directions.

Theoretical background

Cognitive absorption theory

The cognitive absorption framework introduced by Agarwal and Karahanna (2000) refers to a state of total engagement in an activity, involving five dimensions: temporal dissociation, focused IM, heightened enjoyment (HE), control (CO) and curiosity (CU). In educational technology, these dimensions are crucial for understanding how students interact with digital tools and how such interactions enhance cognitive engagement. Cognitive absorption theory posits that the more absorbed individuals are, the more deeply they process information, resulting in better learning outcomes.

Recent research supports the theory's relevance in AR-facilitated learning. For example, these studies (Akçayır & Akçayır, 2017) found that higher levels of focused IM and CO in AR environments improved critical thinking and retention of complex scientific concepts. Similarly, HE and CU – two key dimensions of cognitive

absorption – have been shown to increase cognitive engagement in AR-based lessons, suggesting that AR's immersive nature promotes deeper cognitive processing (Alkhabra et al., 2023).

The cognitive benefits (CBs) of AR include enhanced engagement, memory retention, critical thinking and problem-solving (Guerra-Tamez, 2023). These outcomes are often mediated by students' level of absorption. When students are fully immersed in AR tasks, they may lose track of time, leading to heightened attention and stronger knowledge retention (Alkhabra et al., 2023). Put simply, AR's stimulation of visual and kinaesthetic modalities fosters a sense of control and enjoyment, facilitating the understanding of complex ideas. Thus, cognitive absorption offers a valuable lens to examine AR's cognitive impact. As educational technology evolves, integrating this theory into AR research will be key to designing more immersive and effective learning experiences.

Technology acceptance model

The Technology Acceptance Model (TAM) (Davis, 1989) has long been foundational for understanding users' adoption of new technologies. It proposes that perceived usefulness (PU) and perceived ease of use (PEOU) are the primary determinants of users' intentions to adopt a technology. PU refers to the extent to which a student believes using AR will improve academic performance. When AR is perceived as beneficial, students are more likely to engage with it, leading to enhanced cognitive outcomes. PEOU, meanwhile, refers to the belief that using AR will require minimal effort – a key factor in determining willingness to interact with AR platforms in learning environments.

Recently, researchers have applied TAM to AR-based learning to examine how immersive technologies affect user acceptance and learning outcomes. AR enriches education by merging interactive three-dimensional (3D) elements with the real world, helping students better grasp abstract concepts. For instance, Shyr et al. (2024) found that both PU and PEOU significantly predicted students' intention to use AR for learning.

To reflect the complexity of immersive environments, researchers have extended TAM by incorporating constructs like perceived enjoyment (PE). These extensions provide a more detailed understanding of how AR's engaging features influence learning. Koutromanos et al. (2024), for example, introduced PE into TAM and found that enjoyment positively influenced student engagement and learning in AR-based history lessons. IM – defined as deep involvement in the AR environment – is central to AR's CBs, such as improved conceptual understanding and problem-solving (Guerra-Tamez, 2023). Thus, TAM remains an effective model for examining students' acceptance of AR in immersive learning, and it will continue to be relevant as AR becomes more widespread in education.

Research model and hypotheses development

The developed AR

This research utilises AR learning media previously developed as part of a larger study to examine how this technology can benefit the learning outcome for university students (Khosin et al., 2025; Mahmud et al., 2024). However, when it comes to a better comprehension of the impact of technology developed to address one particular

problem, robust and rigorous validations are required iteratively in the socio-demographic settings. The design of AR itself leverages Mywebar, a web-based application dedicated to developing AR technologies. It is an open-source AR platform that enables the creation of marker-based AR experiences without requiring specialised programming knowledge (Mywebar, 2024).

For the 3D assets, the Blender application, a free and open-source 3D computer graphics software toolset, is employed (Blender, 2024). All the material objects are built using Blender as 3D assets, e.g. inclined cars, helium molecules and solar eclipse phenomena. This is, for instance, shown in Figure 1.

We follow the instructional module supervised by the subject lecturers. Once all the required 3D assets are completely developed, they are subsequently transferred to the Mywebar application to be later customised. The students can then access the AR-formed learning material through a QR code using their smartphones, as shown in Figures 2 and 3. Students who completed learning the subject in the AR environments are asked to fill out a questionnaire previously prepared to capture their over-reaching knowledge from this learning experience.

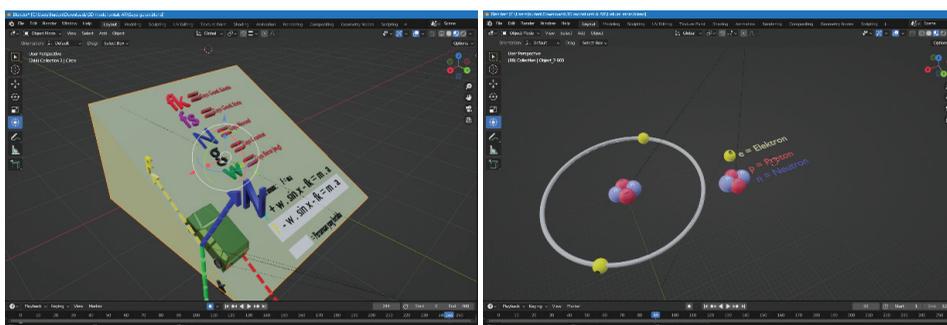


Figure 1. The instances of 3D learning material assets developed in the Blender application. 3D: three-dimensional.

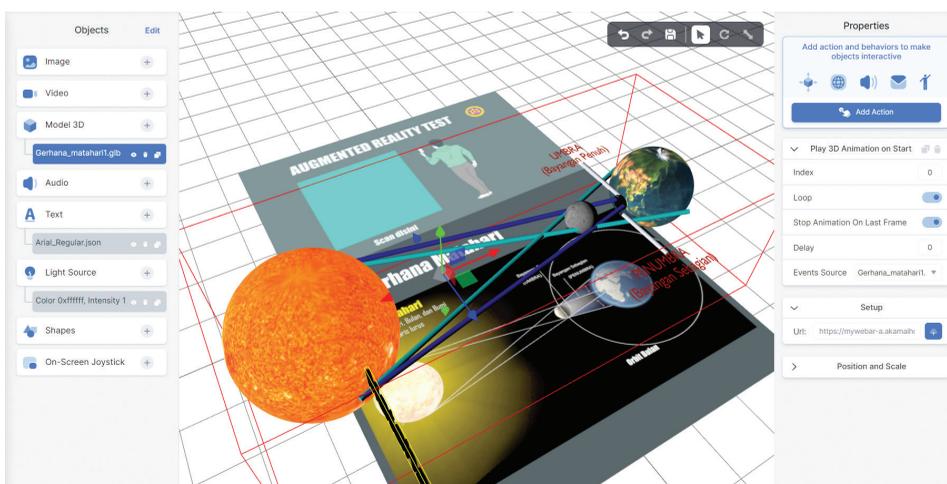


Figure 2. 3D asset of Solar Eclipse created using Blender application. 3D: three-dimensional.

Research model and hypotheses development

As in Figure 4, cognitive absorption is a fundamental determinant of the PU and ease of use of AR-formatted media learning, which subsequently affects the CB students perceive through the level of their states of IM. Previous studies have revealed a significant statistical relationship between HE and PEOU in the context of using new technology, such as the intention to use the world wide web (Agarwal & Karahanna, 2000).

However, these previous studies mostly encapsulated HE into cognitive absorption as a second-order construct, making it hard to conclude the effect of it alone on technology usage (Hou et al., 2019; Jumaan et al., 2020). Others incorporate cognitive absorption into the other existing theories (Tan et al., 2024) that the relationship between HE and PEOU and usefulness cannot be observed directly. Withstanding these, in the context of the present study, we postulate that digitally augmented ARs are aimed to instigate an individual’s subjective enjoyment. Their interactions might affect their perceptions of the technology’s usefulness and ease of use. Therefore, we hypothesise that:

- H1: Heightened enjoyment significantly influences the perceived usefulness*
- H2: Heightened enjoyment significantly influences the perceived ease of use*

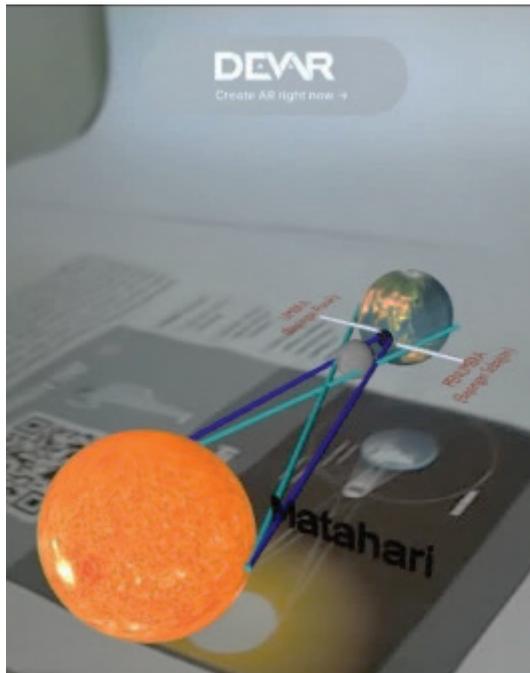


Figure 3. AR display using Mywebar visualised using student’s mobile phone. AR: augmented reality.

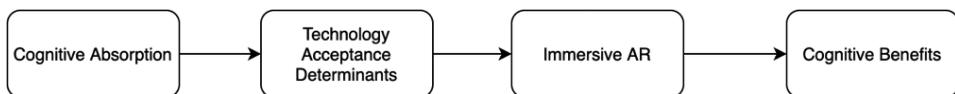


Figure 4. Proposed research model.

Perceived control is about the user's perception of being in charge of the interaction with the AR learning media. Agarwal and Karahanna (2000) have shown that cognitive absorption has a significant impact statistically on the PEOU and usefulness. However, since perceived control of AR media learning is encapsulated as a second-order construct, its effect on PEOU and PU is not clear. Thus, it is safe to say that full control over the interactions between a user and the technology positively influences the PU and PEOU. Therefore, we hypothesise that:

H3: Control significantly influences the perceived usefulness

H4: Control significantly influences the perceived ease of use

Agarwal and Karahanna (2000) have shown that CU enhances cognitive engagement with technology, leading to an increase in PEOU and PU. Thus, individuals who have a profound CU about the AR learning media are likely to undertake a more thorough investigation of its capabilities. The fact that this technology facilitates their cognitive ability effectively in achieving learning materials has been corroborated by studies on technology adoption that demonstrate how CU-driven engagement leads to a more favourable evaluation of the educational effectiveness of the system (Tan et al., 2024). Students conceive AR's ability to facilitate and enhance a better learning process when they realise that it allows them to explore and gain information in new and unique ways. Thus, drawing upon this literature, we test the following:

H5: Curiosity positively influences the perceived usefulness

H6: Curiosity positively influences the perceived ease of use

When individuals experience complete IM in an activity, their cognitive focus shifts exclusively to the task at hand, resulting in a state of absolute absorption (Limongi et al., 2024). The IM provided by AR media is crucial due to its dynamic, engaging and interactive nature. Previous research has established that focused IM enhances PEOU by making the user experience more natural and comprehensible (Wong et al., 2023). Learners are more inclined to perceive AR as user-friendly when they are completely immersed in the environment, hence making the interface seem more intuitive and effortless to use (Limongi et al., 2024). Furthermore, users may fully comprehend the educational significance of the AR system via focused IM, which positively influences PU (Wong et al., 2023). By engaging in the AR experience, students may enhance their understanding and retention of the subject, leading to enhanced learning outcomes. Accordingly, we test that:

H7: Focused immersion significantly influences the perceived usefulness

H8: Focused immersion significantly influences the perceived ease of use

According to the TAM (Davis, 1989), people are more likely to consider a technology to be advantageous if it is easy to use. The degree of PEOU of a system directly affects the degree to which one believes the technology is useful in enhancing performance. Empirical research consistently demonstrates that users experience enhanced cognitive engagement and improved learning outcomes when using AR technology. Şakir (2025) found significant positive correlations between AR's usefulness, ease of use and their behavioural intentions. Similarly, previous studies also show that this technology positively impacts student cognitive strategies, perception and engagement

with technology, learning tasks (Aldeeb et al., 2024), interactivity and learning motivation (Ghobadi et al., 2023; Gill et al., 2025) and learning self-efficacy (Reeves et al., 2021; Shyr et al., 2024), to name a few. In addition, the benefits and applicability of AR technology can also be observed in many technical contexts and across diverse educational settings (Gandolfi & Ferdig, 2025; Singh & Ahmad, 2024).

By enabling seamless and engaging interactions, these technologies enhance the process of learning when they are designed especially to be readily understood and accessible by users. In this context, students are more likely to be drawn into the AR environment and feel more fully immersed if they see AR as a tool for effectively teaching difficult concepts, visualising complex ideas and offering interactive learning possibilities. This translates into a deeper interaction with the provided information. Because of their cognitive ease, they are able to focus on the provided material and engage with the AR environment. Once students are at ease exploring and adjusting AR environment components, they may customise the experience to meet their individual learning needs. Hence, in this study, we also test that:

H9: Perceived ease of use significantly influences the AR perceived usefulness

H10: Perceived usefulness positively influences AR immersion

H11: Perceived ease of use positively influences AR immersion

AR is a promising educational technology that might potentially transform the learning process by offering immersive experiences (Wang et al., 2023). However, recent empirical evidence suggests that AR's greatest potential lies in its ability to significantly influence cognitive processing benefits for learners through multiple mechanisms. Rahimi et al. (2025) found that AR learners demonstrated elevated attention and meditation levels whilst reporting reduced fatigue and exhaustion compared to traditional learning methods. Furthermore, studies examining AR's impact on cognitive load demonstrate that well-designed AR environments can reduce extraneous cognitive load whilst enhancing germane cognitive load, leading to improved learning outcomes (Buchner et al., 2022; Chang et al., 2022; Garzón & Acevedo, 2019). These findings are supported by neurological studies showing increased activation in brain regions associated with attention and memory processing during AR-based intervention (Alessa et al., 2023; Ardecani et al., 2025). This essentially is the main emphasis of this study's contribution. Thus, drawing upon this literature, we test that:

H12: AR immersion significantly influences cognitive benefits in the learning process

Research methodology

Sample

The samples were obtained through a questionnaire developed using Google Forms. Respondents were students from the Faculty of Education of Universitas Papua who voluntarily participated in this research. They are from six education departments: Indonesia language, English, Physics, Chemistry, Mathematics and Biology. Their socio-demographics are described in Table 1. A total of 184 respondents completed the questionnaire.

Table 1. Social-demographic respondents.

Category	Item	Percentage
Gender	Male	32.1
	Female	67.9
Age	<21 years old	37.0
	21–25 years old	60.3
	>25 years old	2.7
Education	High school	96.7
	Diploma	3.3
Department	Mathematics education	27.2
	Chemistry education	2.7
	Physics education	3.3
	Biology education	14.7
	English education	27.7
	Indonesian language education	24.5

Given that this is a quantitative study, an adequate sample size is essential. We adhere to a rigorous protocol to determine it, as advocated here (Goodhue et al., 2012). The responses are evaluated on a Likert scale consisting of five points: from complete disagreement (1) to complete agreement (5). Before the questionnaire was distributed, it underwent a pilot test.

Analysis method

In this study, we utilise SmartPLS 4.0's partial least square-structural equation modelling (PLS-SEM) as an analysis tool. SEM consists of two unique model types: the measurement model and the structural model, also known as the outer model and the inner model (Hair et al., 2019). The measurement model highlights the theoretical connections amongst components of a path model, whilst the structural model illustrates the relationships between constructs.

Data analysis and result

Measurement model evaluation

We follow the PLS-SEM guideline (Hair et al., 2019) to report the analysis and results of this study. This is simply to clarify and acknowledge the methodology used and mitigate the different outcomes and uncertainty that come with other statistical methods, as reported here (Sarstedt et al., 2024). The assessment of the measurement model is the first step in the data analysis process. The objective is to verify the validity and reliability of the measurement items that constitute the proposed model representing the latent variables. This is seen in Table 2.

According to Table 2, factor loadings are often deemed acceptable when above 0.7 (Hair et al., 2019). The initial criterion assessed in the measurement model evaluation is the internal consistency reliability of the constructs. All the Cronbach's Alpha (CA) and Composite Reliability (CR) values indicating internal consistency reliability exceed 0.7, which is deemed satisfactory. The subsequent criterion for measurement is convergent validity. All the Average Variance Extracted (AVE)

values for the constructs exceed 0.5, indicating satisfactory results. The subsequent criterion is to conduct an evaluation of discriminant validity. This is based on the Fornell-Larcker criterion (Hair et al., 2019). Table 3 demonstrates that discriminant validity is firmly established, as the square root of AVE for each construct is greater than that particular construct's correlations and other constructs.

Structural model evaluation

The next was evaluating the structural model. The structural model evaluation is calculated using bootstrapping 5000 subsamples, one-tail and bias-corrected and accelerated of 5% for the confidence interval. The result is presented in Figure 5.

Common method bias

Common method bias (CMB) was assessed (Podsakoff et al., 2003) due to the collection of all variables in a single survey. The results of Harman's single-factor analysis indicated that all variables account for 47.71% of the total variance. This value is below 50%, suggesting that CMB is unlikely to be a concern and is not expected to affect the research outcomes of this study. Second, we proceed with this using the Variance Inflation Factor (VIF) (Benitez et al., 2020; Hair et al., 2019). Our evaluations show VIF values range between 1.00 (IM-CB, the lowest) and 2.888 (PEOU-PU, the

Table 2. Values of Cronbach's alpha, composite reliability and average variance extracted.

Construct	CA	CR	AVE
Heightened enjoyment (HE)	0.840	0.845	0.758
Control (CO)	0.786	0.793	0.700
Curiosity (CU)	0.775	0.784	0.689
Focused immersion (FI)	0.806	0.807	0.721
Perceived usefulness (PU)	0.680	0.684	0.611
Perceived ease of use (PEOU)	0.749	0.751	0.666
Immersion AR (IM)	0.755	0.756	0.672
Cognitive benefits (CB)	0.755	0.765	0.670

AR: augmented reality.

Table 3. Discriminant validity of the construct level.

Construct names	CB	CO	CU	FI	HE	IM	PEOU	PU
CB	0.819							
CO	0.720	0.837						
CU	0.645	0.631	0.830					
FI	0.741	0.749	0.624	0.849				
HE	0.647	0.672	0.630	0.705	0.871			
IM	0.743	0.668	0.638	0.735	0.779	0.819		
PEOU	0.656	0.693	0.643	0.684	0.752	0.768	0.816	
PU	0.684	0.682	0.663	0.643	0.711	0.680	0.678	0.782

Discriminant validity is significant as the square root of AVE for each construct is greater than that particular construct's correlations and other constructs.

HE: heightened enjoyment; CO: control; CU: curiosity; FI: focused immersion; PU: perceived usefulness; PEOU: perceived ease of use; IM: immersion; CB: cognitive benefits.

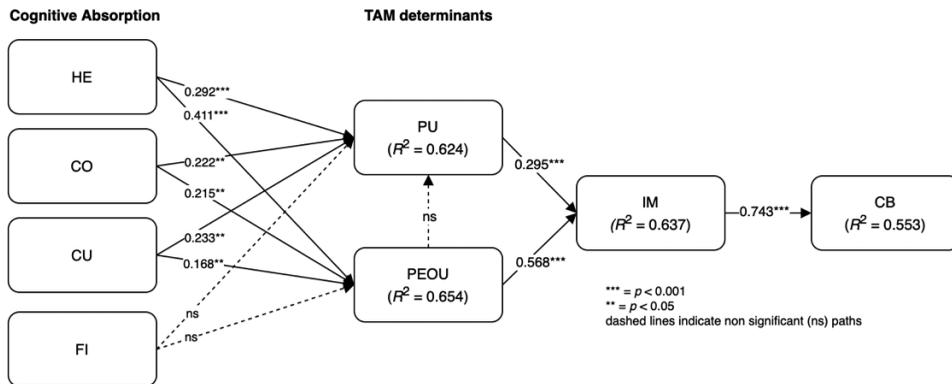


Figure 5. Hypotheses evaluation. HE: heightened enjoyment; CO: control; CU: curiosity; FI: focused immersion; PU: perceived usefulness; PEOU: perceived ease of use; IM: immersion; CB: cognitive benefits.

highest), indicating there are no multicollinearity issues as correlations amongst the variables are lower than the threshold of 3.3 (Kock, 2015).

Multi-group analysis

In the last part of the analysis, we examined the multi-group analysis (MGA) between students in natural science (Mathematics, Chemistry, Physics and Biology) and social science (English and Indonesian languages) departments in terms of the impact of cognitive absorption on learning outcome through the learning processes utilising AR technology. We follow the guidelines described here (Cheah et al., 2020). The results show that there is no difference between these two groups, as all the relations are insignificant ($p > 0.05$). This implies both theoretically and practically. We discuss these in the following sections.

Discussions and conclusions

The analysis reveals a significant effect of HE on both PU and PEOU (H1: $\beta = 0.292$, $p < 0.001$; H2: $\beta = 0.411$, $p < 0.001$). This indicates that when students enjoy using AR in their learning, they are more inclined to view it as both beneficial and user-friendly. This finding is in line with recent studies emphasising enjoyment’s critical role in educational technology adoption. For instance, Boel et al. (2023) found that AR-enhanced language learning, when enjoyable, not only increased engagement but also improved the perceived effectiveness of the technology by both students and teachers. Similarly, Wang et al. (2023) demonstrated that enjoyment, represented through flow experiences in mobile AR, boosts learning effectiveness, satisfaction and reduces cognitive load – allowing learners to focus more on content than interface complexities (Thees et al., 2020).

The sense of CO also has a significant impact on both PU (H3: $\beta = 0.222$, $p = 0.010$) and PEOU (H4: $\beta = 0.215$, $p = 0.003$). Similarly, CU significantly affects both PU (H5: $\beta = 0.223$, $p = 0.006$) and PEOU (H6: $\beta = 0.168$, $p = 0.009$). These findings suggest that students who feel in control of their AR interactions and are curious about the technology perceive it as more useful and easier to use. Akçayır and Akçayır (2017) support this by showing that interactive control over AR enhances

learning outcomes and satisfaction. Furthermore, CU, as emphasised by Alkhabra et al. (2023), plays a vital role in stimulating engagement and improving knowledge retention, reinforcing its importance in AR-based learning environments.

Conversely, this study found no significant effect of focused immersion (FI) on either PU (H7) or PEOU (H8), contrasting earlier findings such as those by Uriarte-Portillo et al. (2022), who linked immersive learning profiles to improved outcomes. This disparity might stem from the multidimensional nature of IM. Although FI enhances engagement, it may not necessarily influence perceptions of utility or usability. The variance may also relate to the novelty or complexity of the AR system used, potentially causing students to rely more on enjoyment, CO or CU rather than IM alone. The non-significant result of H9 (PEOU → PU) is another important observation. Whilst TAM generally posits a relationship between ease of use and usefulness (Limongi et al., 2024), the AR context may differ. Shyr et al. (2024) argue that the perceived innovativeness of AR may outweigh usability when students assess usefulness.

Nevertheless, the significant effects of PU and PEOU on IM (H10: $\beta = 0.295$, $p < 0.001$; H11: $\beta = 0.568$, $p < 0.001$) show that students who find AR is useful and easy to use are more likely to become fully immersed. Wong et al. (2023) found similar links between perceived ease, utility and immersive learning experiences. The strongest relationship is from IM to CB (H12: $\beta = 0.743$, $p < 0.001$), suggesting that IM greatly enhances understanding, retention and application of knowledge. This aligns with these findings of Tursunova et al. (2024) who highlight AR's potential to improve cognitive outcomes. Finally, a MGA comparing students from natural and social sciences revealed consistent relationships across all latent variables. This challenges perspectives like Rozgonjuk et al. (2020), who suggest cognitive and learning process differences between STEM and social science students. In this study, AR-based learning appears to bridge those disciplinary differences, supporting its broad applicability.

To further explore the findings from the structural equation model, an importance-performance map analysis (IPMA) is used, as shown in Figure 6. The aim is to assess the significance and performance of model constructs, offering valuable guidance for educational improvements.

The IPMA highlights IM as the most influential factor on CBs in AR-based learning (effect = 0.743) but with relatively low performance (76.902), suggesting a need to enhance interactivity. PEOU also significantly affects learning (effect = 0.451) and should be improved by simplifying AR interfaces. HE moderately impacts learning (0.249) and helps sustain motivation, so it should be maintained. Whilst CU and CO show high performance, their effects are weaker, making them lower priorities. PU shows a moderate effect and strong performance. Overall, improvements in IM and PEOU, along with maintaining HE and emphasising PU, are key to optimising AR's educational impact.

Theoretical implications

Grounded in Cognitive Absorption Theory, this study offers meaningful theoretical advancements in understanding how AR supports learning, particularly cognitive development. It extends traditional TAMs by incorporating emotional and motivational factors, especially relevant for immersive tools like AR. Whilst cognitive absorption has traditionally emphasised deep engagement with technology (Agarwal & Karahanna, 2000), our findings emphasise that emotional drivers – such as enjoyment, CU and CO – play a vital role in fostering such

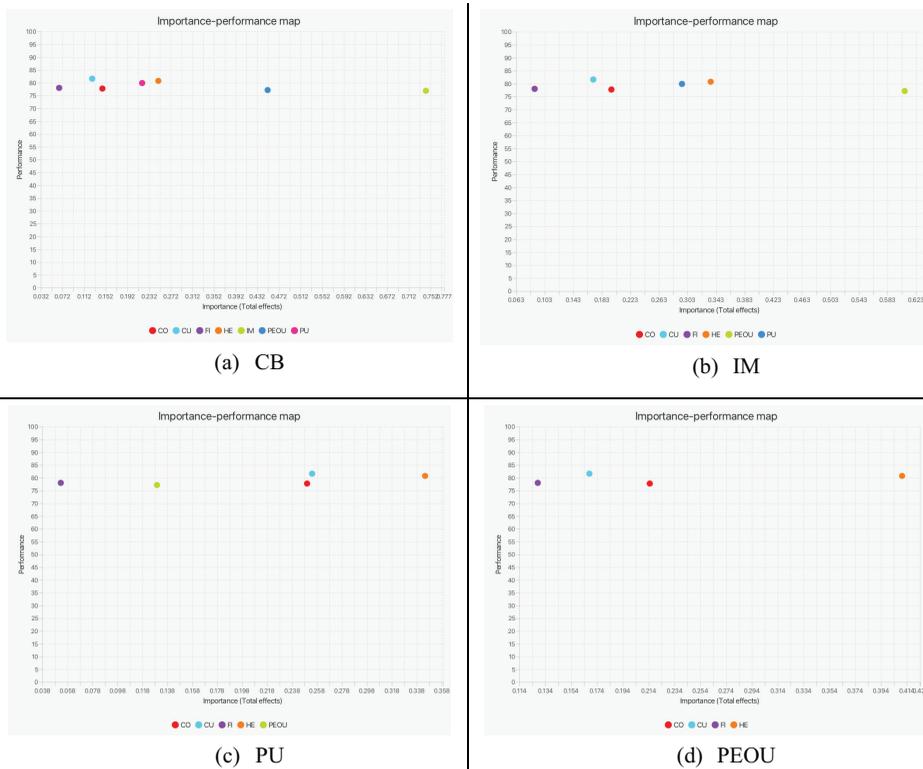


Figure 6. IPMA for (a) cognitive benefit (CB), (b) immersion (IM), (c) perceived usefulness (PU) and (d) perceived ease of use (PEOU). IPMA: importance-performance map analysis.

engagement (Guinaliu-Blasco et al., 2019). This reframes cognitive absorption as not merely a product of IM but a result of emotional involvement with AR environments. Studies such as Sadan et al. (2024) further validate that emotional experiences like enjoyment enhance digital learning outcomes. Our research confirms that enjoyment, CU and CO significantly influence PEOU and PU, both precursors to IM.

Interestingly, the rejection of H9 (PEOU → PU) challenges a central tenet of the TAM (Davis, 1989), which posits a direct link between ease of use and usefulness. In the context of AR, this connection weakens – likely because engagement factors like enjoyment overshadow usability in shaping perceptions of value. Shyr et al. (2024) found similar outcomes, where novelty and interactive engagement in AR environments outweighed the importance of simplicity.

Furthermore, the strong impact of emotional engagement on cognitive absorption signals the need for future theoretical models to move beyond purely cognitive or behavioural explanations. Our proposed framework integrates both emotional and cognitive pathways.

Finally, the MGA reveals that AR benefits students equally across STEM and social science disciplines. This challenges the assumption that AR suits STEM subjects better, suggesting AR’s universal potential in enhancing cognitive outcomes and learner engagement across fields.

Practical implications

This research offers valuable practical insights for educators, instructional designers and AR developers aiming to improve learning experiences and cognitive outcomes. A key finding is the strong impact of HE on both PU and PEOU, suggesting that AR learning tools should prioritise engaging, enjoyable experiences. Designing playful and accessible AR content can enhance perceived value, as emphasised by Basumatary and Maity (2023).

Equally important are the roles of CO and CU in improving PU and PEOU. AR tools should allow learners to explore freely, set their own learning pace and make autonomous decisions. Integrating gamification or open-ended tasks can foster CU and deeper engagement. Lin et al. (2022) found that giving learners CO in AR-based science learning increased their engagement and learning outcomes. Similarly, CU-driven AR learning led to better retention and involvement (Alkhabra et al., 2023).

The strong path from IM to CB highlights the value of deeply engaging AR experiences. Developers should focus on multi-sensory environments – visual, auditory and tactile – that simulate real-world settings or allow interaction with 3D objects. Balushi et al. (2024) reported that such immersive features boost motivation, retention and comprehension.

For policymakers, this study underscores the need to support AR integration through infrastructure, teacher training and pedagogy focused on HE, CU and IM. IPMA results further show that PEOU and IM are the most critical drivers of CBs and should be central to AR design strategies.

Limitations and future research directions

Limitations

Whilst this research offers important contributions, it also faces several limitations that must be acknowledged. First, this study focuses on a specific set of variables related to the cognitive absorption approach, potentially overlooking other factors that might influence the effectiveness of AR in learning, such as technology experience or cultural. Future studies could broaden the scope by including additional variables that may impact learning outcomes. Second, the sample used in the study may limit the generalisability of the findings. This study was conducted within a specific educational context or demographic, that is students from only one faculty (Education Faculty, Universitas Papua, Indonesia). This does not reflect the diversity of learners in other environments and learning styles. A more diverse sample across various educational settings and subjects would provide a more comprehensive understanding of AR's impact on learning. Finally, the cross-sectional nature of the study means that the relationships between the variables were captured at a single point in time. This limits the ability to establish causality between the variables.

Future research directions

Whilst this research provides significant insights into the role of AR in improving CBs, there remains much to explore. For instance, examining how learners' emotions, such as frustration or anxiety, influence their engagement with AR tools would help refine the understanding of the emotional dimensions of AR

in learning. Furthermore, future research could investigate whether the cognitive gains observed in immersive AR environments persist over time and how continued use of AR tools impacts learners' motivation and academic performance in the long run. Collaboration in AR environments is another promising area for future research. Whilst this study focused primarily on individual cognitive absorption, collaborative learning through AR could foster peer-to-peer interaction, knowledge sharing and collective problem-solving, leading to enhanced learning outcomes (Inan et al., 2023).

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