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Enhancing Pedagogical Design through Students' Engagement in Augmented Reality Learning: Evidence from a Validated Cognitive–Affective Framework

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Abstract. This study explored how students' engagement in augmented reality (AR)-based textbook learning can inform effective pedagogical design through a validated cognitive–affective framework. Grounded in the cognitive theory of multimedia learning (CTML) and the technology continuance theory (TCT), the research examined how cognitive and emotional factors jointly shape students' engagement and their sustained intention to learn with AR. A quantitative survey involving 100 secondary students was conducted to validate six key constructs: visual attraction, knowledge capability, situational experience, attitude, satisfaction, and continuance intention. Exploratory factor analysis (EFA) confirmed the reliability and theoretical coherence of the model. The findings revealed that meaningful AR learning arises when multimedia design supports cognitive processing while emotional satisfaction sustains motivation. The validated framework provides educators and curriculum developers with practical guidelines for designing AR-enhanced textbook materials that balance mental effort and emotional engagement. This study contributes empirical evidence and pedagogical insight into how AR technology can enrich classroom learning through both cognitive effectiveness and affective fulfilment.

Keywords: Augmented Reality; Student Engagement; Cognitive–Affective Framework; Pedagogical Design; Multimedia Learning

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1. Introduction

The rapid development of digital technologies has markedly altered global education systems, compelling schools to incorporate emerging tools such as augmented reality (AR), virtual reality (VR), artificial intelligence (AI) and mobile learning platforms (Ibrahim et al., 2024). This transformation is consistent with Malaysia's National Digital Education Policy (Kementerian Pendidikan Malaysia, 2023) and the Education Strategic Plan 2024–2030, which highlight the importance of technology integration to foster innovative, future-ready learning. In this context, augmented reality has attracted increasing interest for its ability to improve engagement, conceptual understanding and learner motivation through immersive, multimodal experiences.

In Malaysia, various studies have investigated the educational benefits of augmented reality and other immersive technologies in improving students' learning outcomes. Helmi et al. (2022) demonstrated that AR-based instructional design enhanced motivation and interactivity among secondary students. In contrast, while Jaaffar and Adnan (2025) emphasised the significance of pedagogical alignment and teacher readiness for the successful implementation of AR. However, despite these promising findings, the integration of augmented reality in Malaysian schools is constrained by various factors, such as the absence of user-friendly applications, inconsistent teacher preparedness and apprehensions regarding cognitive load (Buchner et al., 2022). These challenges indicate a necessity for pedagogically informed strategies that integrate technology with significant learning experiences.

Augmented Reality is increasingly acknowledged as an effective pedagogical tool that promotes student-centred learning, allowing learners to engage with complex or abstract concepts via interactive 3D representations (Cao & Yu, 2023; Jaaffar & Adnan, 2025). The effectiveness of these experiences relies on robust pedagogical design that harmonises cognitive and emotional engagement. The cognitive theory of multimedia learning (CTML) posits that learning is enhanced through the effective integration of visual and verbal information, which minimises cognitive overload and enhances retention (Mayer, 2008). The technology continuance theory (TCT) (Liao et al., 2009) elucidates learners' persistent intention to utilise educational technologies, highlighting satisfaction and attitude as critical mediating factors in continued engagement.

The integration of these two frameworks offers a dual perspective for analysing students' engagement with AR. CTML examines the role of multimedia design in facilitating cognitive processing (Mayer, 2008), whereas TCT highlights the affective and motivational factors that influence students' continued engagement with the technology (Liao et al., 2009). The convergence of these viewpoints indicates that successful AR learning experiences should efficiently communicate information while also stimulating curiosity, satisfaction and enjoyment, as supported by prior multimedia learning and technology continuance research. This approach aligns with contemporary pedagogical trends that emphasise active, learner-centred and emotionally engaging education.

Although numerous international studies have validated AR-related scales and examined learners' attitudes toward immersive technologies (e.g., Chen et al., 2021; Kruger & Bodemer, 2022; Rangel-de Lázaro & Duart, 2023), these studies predominantly involve university or adult learners. Very few have focused on younger secondary students, particularly within Southeast Asian contexts, where curriculum structures, cultural expectations and technology access differ significantly. This gap indicates a need for research that validates AR engagement constructs specifically for lower-secondary learners in Malaysia. Previous validations primarily involved university or vocational students, whose cultural, linguistic, and curricular contexts significantly differ from those in secondary schools (Chen et al., 2021; Helmi et al., 2022).

In Malaysia, several studies have explored the use of AR and immersive technologies in education, particularly in examining motivation, readiness and teacher-related factors (e.g., Ahmad & Abu Samah, 2024; Helmi et al., 2022; Norman, 2025). However, these works primarily address general attitudes or pedagogical challenges rather than cognitive and emotional engagement based on validated constructs. Very few studies have examined lower-secondary learners specifically, despite the differences in developmental stage, curriculum requirements and classroom practices. Furthermore, existing Malaysian AR studies rarely link validated engagement constructs to pedagogical design for classroom implementation. Therefore, empirical evidence on the cognitive and emotional engagement of lower-secondary students with AR learning tools remains limited, and little is known about how validated engagement constructs can inform effective AR-enhanced textbook design.

This research addresses existing gaps by creating and validating a bilingual tool designed to assess students' cognitive and affective engagement in AR-based learning. This study interprets the validated constructs as pedagogical indicators, providing educators with practical insights on the design and implementation of AR to enhance motivation, understanding and sustained learning interest. This research, rooted in the cognitive theory of multimedia learning (CTML) (Mayer, 2008) and the technology continuance theory (TCT) (Liao et al., 2009), offers theoretical and practical contributions to the incorporation of immersive technologies in education, in accordance with Malaysia's national agenda for digital transformation and 21st-century learning.

The conceptual framework illustrated in Figure 1 integrates CTML, which explains how cognitive processing supports meaningful learning through well-designed multimedia (Mayer, 2008) and TCT, which highlights the affective and motivational aspects that sustain technology use (Liao et al., 2009). Together, these theories provide a comprehensive perspective for understanding students' engagement with AR-based learning environments.

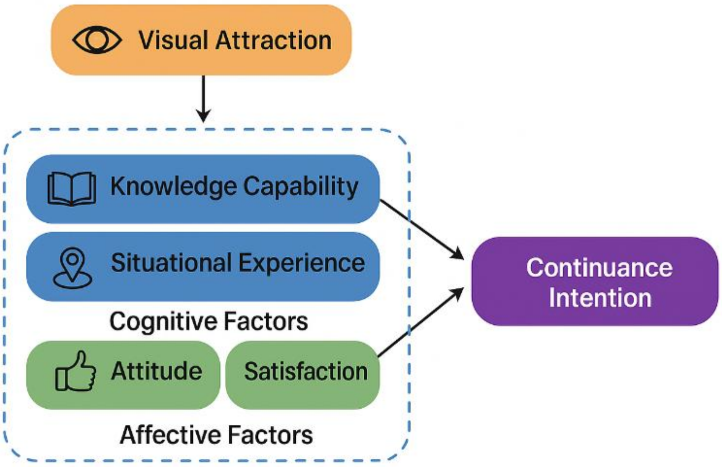

Figure 1: Conceptual framework integrating CTML and TCT for investigating students' engagement with AR learning

2. Literature Review

2.1 Augmented Reality in Education

Augmented Reality (AR) overlays digital elements—such as 3D models, animations, text, or audio—onto real-world environments in real time, allowing learners to interact simultaneously with both virtual and physical components. In the field of education, augmented reality has shown promise in boosting learning motivation, improving conceptual understanding and increasing engagement (Chen et al., 2021; Kruger & Bodemer, 2022). This approach allows students to better understand abstract concepts, engage with virtual objects and interact with educational materials in a more intuitive manner (Cao & Yu, 2023). This immersive experience demonstrates how AR aligns with the principles of student-centred learning and effectively supports differentiated instruction.

The incorporation of augmented reality in secondary education in Malaysia is still in its nascent phase. The National Digital Education Policy (Kementerian Pendidikan Malaysia, 2023) and the Strategic Plan 2024–2030 advocate for digital transformation in education; however, implementation has faced constraints related to infrastructure, readiness and pedagogical challenges (Buchner et al., 2022). Educators frequently encounter challenges in choosing or creating augmented reality content that aligns with curriculum goals, while learners may suffer from heightened cognitive load resulting from the unfamiliarity of the technology (Helmi et al., 2022). Empirical research on students' readiness and behavioural intention to utilise augmented reality is crucial for informing effective integration into educational practices.

2.2 Theoretical Foundation

The cognitive theory of multimedia learning (CTML), proposed by Mayer, (2008), clarifies how learners integrate information through verbal and visual modalities. CTML is pertinent to our study as AR-based textbook learning conveys knowledge via integrated 3D visualisations such as interactive models, animations, or objects that appear on top of the textbook pages when scanned through a mobile device and supplementary textual explanations. The dual channels mitigate cognitive burden and facilitate meaningful learning, especially when abstract concepts are represented through augmented reality. Consequently, CTML offers a theoretical framework for comprehending the impact of AR design on students' cognitive engagement in this research. CTML posits that effective multimedia learning is achieved when both channels are balanced, cognitive overload is minimised and information is presented in an integrated and meaningful manner. In augmented reality learning, students engage with 3D visualisations alongside textual or auditory explanations, potentially improving retention and comprehension when designed effectively (Ke & Hsu, 2015). Poorly designed AR applications can, however, overwhelm working memory, resulting in decreased learning efficiency (Sweller, 2017). CTML offers a theoretical framework for evaluating the impact of visual and interactive elements of AR on students' learning experiences and motivation.

The technology continuance theory (TCT) proposed by Liao et al. (2009) builds upon the technology acceptance model (TAM) by elucidating users' ongoing intention to utilise a technology after its initial adoption. The theory suggests that satisfaction and attitude serve as mediators between users' perceptions, including usefulness and ease of use, and their intention to persist in using the technology. TCT holds significant importance in educational settings where sustained interaction with digital tools is crucial for achieving effective learning outcomes.

In augmented reality-based learning, student satisfaction and attitudes towards the technology influence their ongoing engagement in future learning activities (Zareravasan & Ashrafi, 2019). The integration of CTML and TCT provides a dual perspective: CTML focusses on cognitive and design aspects of learning (Mayer, 2008), while TCT analyses behavioural and motivational factors influencing technology use (Liao et al., 2009). Previous research indicates that multimedia design affects cognitive processing and comprehension, while user satisfaction and perceived usefulness influence technology continuance behaviour, thereby endorsing the integrated application of both theories in technology-mediated learning contexts.

2.3 Key Constructs in AR-Based Learning

Visual attraction denotes the extent to which augmented reality (AR) content engages students' attention and fosters interest via design, colour, motion and interactivity. Kruger and Bodemer, (2022) assert that effective visual design in augmented reality learning environments enhances engagement and facilitates cognitive processing by guiding learners' attention to pertinent information. In the context of Malaysia, visually engaging augmented reality materials can enhance motivation among students familiar with digital media consumption beyond the classroom (Saili et al., 2018). Visual attraction is proposed as a key factor affecting satisfaction and attitudes towards the use of augmented reality.

Knowledge capability is how well students think they can learn, remember and use what they learn through AR encounters. It shows that people are confident in their ability to learn the subject matter when they use interactive, visual resources. Chen et al. (2021) discovered that students who viewed themselves as more knowledgeable expressed higher levels of satisfaction and a larger inclination to continue utilising augmented reality (AR) textbooks. This concept is in line with the cognitive theory of multimedia learning (CTML), which focuses on how multimedia display affects cognitive performance (Mayer, 2008).

Situational experience refers to the immersive and contextual characteristics of augmented reality learning, wherein learners engage with virtual components that react to their actual surroundings (Helmi et al., 2022; Kruger & Bodemer, 2022). Favourable situational experience can enhance perceived authenticity and emotional involvement (Marín-Díaz et al., 2022). Nevertheless, such experiences must be meticulously crafted to prevent distraction or cognitive overload. This study considers situational experience as an external element affecting students' attitudes towards the use of augmented reality.

Attitude reflects students' comprehensive positive or negative assessment of AR as an educational instrument. It functions as a pivotal intermediary in TCT, connecting external elements like visual appeal and contextual experience with behavioural intention (Liao et al., 2009). Students' perceptions of augmented reality as beneficial, engaging and user-friendly lead to more favourable attitudes towards its use in education (Zareravasan & Ashrafi, 2019). Attitude is essential in forecasting students' willingness to persist in utilising AR technologies in subsequent courses.

Satisfaction denotes students' emotional response following engagement with augmented reality learning resources, and it includes feelings of pleasure, usefulness and the fulfilment of educational expectations (Liao et al., 2009). Within the context of AR-based learning, satisfaction reflects learners' positive perceptions of the experience and contributes to their intention to continue using the technology (Chen et al., 2021). Previous research demonstrates that pleasure is a crucial factor influencing technology continuance (Chen et al., 2021; Liao et al., 2009). In AR-based learning, satisfaction occurs when the technology improves motivation and comprehension without imposing an undue cognitive burden, consistent with the principles of cognitive load management in multimedia environments (Mayer, 2008). Elevated satisfaction subsequently increases the likelihood of continued engagement with AR solutions, as satisfaction is a key predictor of technology continuance intention (Chen et al., 2021; Liao et al., 2009).

Continuous intention to use denotes the extent to which students plan to persist in utilising AR technology for educational purposes in the future. It signifies the behavioural result of the aforementioned constructs. Zareravasan and Ashrafi, (2019) assert that students' sustained intention is influenced by satisfaction, attitude and the perceived utility of the technology. This study identifies continuous intention as the primary dependent variable, signifying students' preparedness to integrate augmented reality into their learning experience consistently.

2.4 Instrument Development and Pedagogical Alignment

The validity and reliability of instruments are critical in ensuring credible empirical findings in educational research. Cross-cultural adaptation is especially important when measuring constructs such as motivation or engagement in contexts where language and curriculum differ (Taherdoost, 2021).

This study developed the AR Intention Scale by integrating constructs from five established instruments: the Instructional Material Motivation Scale for Single-Use (Barut & Dursun, 2022), the Continuance Intention of AR Textbooks (Chen et al., 2021), the ARcis Questionnaire (Kruger & Bodemer, 2022), the technology continuance theory (Liao et al., 2009) and the Students' Continuation Intention Scale (Zareravasan & Ashrafi, 2019). These instruments established the theoretical basis for quantifying both cognitive and emotional aspects of AR engagement.

The adaptation adhered to established guidelines for translation validity and content relevance, ensuring the items were pedagogically suitable for Malaysian secondary students (Dhamani & Richter, 2011). The adaptation process followed standard criteria for item clarity, linguistic equivalence and contextual appropriateness as recommended for instrument development in educational settings (Hair et al., 2010; Kline, 2015). This step ensured conceptual equivalence across languages and preserved cultural appropriateness.

This section articulates the theoretical justification for aligning each construct, visual attraction, knowledge capability, situational experience, attitude, satisfaction and continuance intention with pedagogical principles informed by CTML and TCT, rather than prioritising psychometric validation (Liao et al., 2009; Mayer, 2008). The instrument serves dual purposes: it acts as a measurement tool and a pedagogical framework for analysing the effects of augmented reality learning environments on student engagement and motivation. This is corroborated by prior research that has employed engagement constructs to inform AR-based instructional design (Barut & Dursun, 2022; Chen et al., 2021).

3. Methodology

3.1 Research Design

This research utilised a quantitative descriptive design based on the cognitive theory of multimedia learning (CTML) and the technology continuance theory (TCT). The dual-theoretical approach directed the examination of students' cognitive and emotional engagement with augmented reality (AR) learning, as CTML explains how cognitive processing occurs in multimedia environments (Mayer, 2008), while TCT highlights the affective and motivational factors that influence continued technology use (Liao et al., 2009). The design sought to validate a measurement instrument while simultaneously offering pedagogical insights into how AR-based textbook learning fosters meaningful engagement, consistent with recent studies demonstrating the role of AR in promoting learner motivation and sustained interaction (Karelkhan & Uderbayeva, 2024; Sakr & Abdullah, 2024).

The methodological process consisted of four phases: (1) instrument development and adaptation; (2) expert review and content validation; (3) pilot testing with secondary students; and (4) data analysis for construct validation and interpretation. Each phase ensured both methodological rigour and pedagogical authenticity by aligning research procedures with actual classroom contexts. Figure 2 illustrates the overall research design, which integrates both theoretical and empirical elements to ensure methodological rigour. The design adopted a sequential explanatory approach, beginning with the conceptualisation of constructs based on the CTML and the TCT, followed by instrument validation and statistical testing using exploratory factor analysis (EFA). This structured process ensured that the developed instrument not only demonstrates reliability and validity but also provides meaningful insights for pedagogical application in AR learning environments.

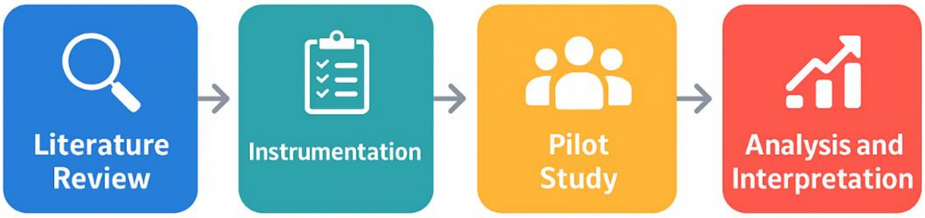

Figure 2: Research Design

3.2 Population and Sample

The population for this study consisted of 95,571 lower secondary students enrolled in public schools across Malaysia. From this population, a sample of 540 Form One students was selected using purposive sampling to represent learners who had been exposed to technology-integrated classroom practices. Prior to the main data collection, a pilot study involving 100 Form One students from a school in Selangor was conducted to assess the clarity, reliability and contextual suitability of the adapted instrument. This age group was pedagogically appropriate as early adolescents benefit from visual and interactive learning environments that enhance comprehension and engagement.

This category signified learners evolving from concrete to abstract reasoning, rendering them appropriate candidates for AR-based textbook study. The sample size was sufficient for exploratory factor analysis (EFA), adhering to the guidelines established by Hair et al. (2010). Ethical approval was obtained from the Ministry of Education Malaysia and the participating school before data collection commenced.

3.3 AR Learning Application

The AR learning module was developed using the Vuforia Engine integrated with Unity 3D, representing an extension of a secondary-level textbook unit. The module aimed to enhance student engagement by transforming static textbook content into interactive 3D experiences. Students utilised mobile devices to scan printed image markers integrated into the textbook, activating 3D animations and interactive elements. The augmented reality situations replicated basic problemsolving scenarios, including movement, sequencing and decision-making activities. These activities implemented CTML principles by integrating visual and verbal channels for enhanced cognitive processing, whereas TCT principles were evident in the emotive components, enjoyment, curiosity and satisfaction that bolstered continuance intention. Figure 3 illustrates the Unity interface used to develop the AR-based textbook learning module. The interface integrates digital 3D models, interactive markers and animation sequences that align with textbook content. The AR design follows the cognitive theory of multimedia learning (CTML) by merging visual and verbal elements to optimise cognitive processing (Mayer, 2008). It also reflects the principles of the technology continuance theory (TCT), ensuring that interaction remains intuitive and enjoyable, thereby fostering sustained engagement and continuance intention (Liao et al., 2009).

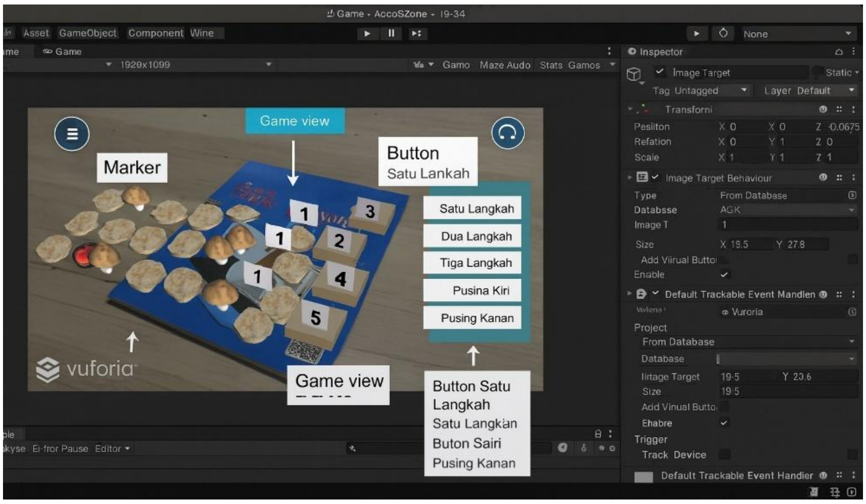

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Figure 3: Interface of the augmented reality (AR) learning application developed using the Vuforia Engine and Unity 3D

Figure 4 demonstrates how students engaged with the AR-based textbook module during the classroom implementation. Using mobile devices, learners scanned printed image markers that activated 3D objects and animations linked to textbook content. The activity allowed students to explore visual and spatial representations of abstract concepts, promoting active participation and inquiry-based learning. From a pedagogical standpoint, this interactive experience supports the principles of CTML by enhancing cognitive processing through visualisation (Mayer, 2008), while also aligning with TCT by fostering motivation and satisfaction through immersive engagement (Liao et al., 2009).

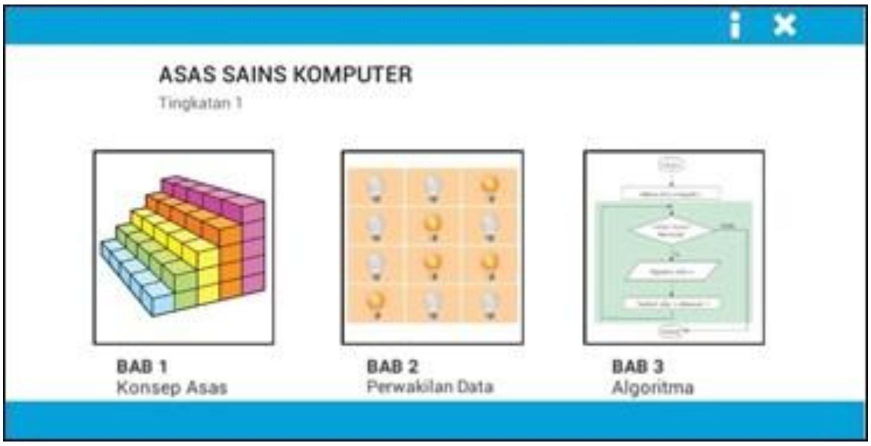

Figure 4: Example of students' interaction with the augmented reality (AR) textbook learning activity

Figure 5 presents the validated six-construct engagement model derived from exploratory factor analysis (EFA). The model integrates the cognitive dimension—comprising visual attraction, knowledge capability and situational experience—and the affective dimension—comprising attitude, satisfaction and continuance intention. Together, these constructs form a holistic framework that explains students' engagement in augmented reality-enhanced textbook learning. The model reflects the integration of CTML, which explains how visual and verbal representations support cognitive processing (Mayer, 2008) and TCT, which posits that satisfaction and perceived usefulness influence users' intention to continue using a technology (Liao et al., 2009). This theoretical alignment demonstrates how cognitive processing and emotional motivation jointly determine students' intention to continue learning with AR technology.

Figure 5: Validated model of students' engagement in AR-based textbook learning

Figure 6 illustrates the conceptual framework connecting CTML and TCT and provides a basis for understanding users' ongoing engagement with digital technologies, including AR-enhanced textbook learning (Liao et al., 2009). The model depicts how cognitive constructs such as visual attraction, knowledge capability and situational experience interact with affective constructs such as attitude, satisfaction and continuance intention to explain students' engagement.

The integration highlighted that effective AR learning occurs when multimedia design principles support mental processing, as proposed in the CTML (Mayer, 2008), while emotional satisfaction sustains motivation and continuance intention, consistent with TCT (Liao et al., 2009). This theoretical convergence provides a pedagogical foundation for developing AR learning materials that are cognitively efficient and emotionally engaging, a relationship supported by recent studies on AR-based learning engagement (Maharjan et al., 2024; Sakr & Abdullah, 2024).

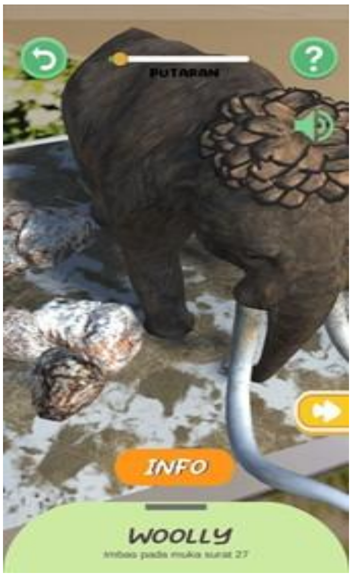

Figure 6: Conceptual integration of CTML and TCT in AR-based textbook learning

3.4 Instrumentation and Pedagogical Alignment

This study utilised an instrument that was adapted and synthesised from five established tools commonly employed in educational technology and user-intention research. The instruments utilised comprised the Instructional Material Motivation Scale for Single-Use (IMMS-SU) by Barut and Dursun, (2022), the Continuance Intention of Augmented Reality Textbooks by Chen et al., (2021), the ARcis Questionnaire by Kruger and Bodemer, (2022), the technology continuance theory (TCT) by Liao et al., (2009) and the Students' Continuation Intention to Use Technology scale by Zareravasan and Ashrafi, (2019). Materials from these sources were evaluated, chosen and adapted to align with the Malaysian secondary education framework.

The final pilot questionnaire comprised 56 items organised into two primary sections. Section A gathered demographic data, including gender, age and technological experience. Section B comprised six latent constructs that represent the primary variables of the study: visual attraction, knowledge capability, situational experience, attitude, satisfaction and continuous intention to use augmented reality (AR). Beyond measurement, the instrument served as a pedagogical diagnostic tool, enabling educators to interpret engagement not only numerically but also as an indicator of how AR-based textbook interactions influence cognitive effort and emotional engagement. Table 1 outlines the structure of the modified questionnaire.

Table 1: Structure of the Adapted Questionnaire

Section	Description	Number of Items	Constructs
A	Demographic Information	7	–
B	AR-Based Learning Constructs	49	Visual Attraction, Knowledge Capability, Situational Experience, Attitude, Satisfaction, Continuous Intention

3.5 Translation and Content Validation

The instrument underwent forward–backward translation by bilingual experts, followed by validation by subject specialists in educational technology. Content validity was assessed using a Content Validity Index (CVI) and expert feedback led to minor revisions to ensure semantic and pedagogical accuracy. Reliability was subsequently examined through Cronbach's alpha, with all constructs exceeding the recommended threshold of .70, indicating satisfactory internal consistency (Hair et al., 2010; Kline, 2015).

The constructs demonstrated strong internal consistency, with reliability coefficients ranging from .783 to .905—visual attraction ($\alpha = .830$), knowledge capability ($\alpha = .783$), situational experience ($\alpha = .804$), attitude ($\alpha = .824$), satisfaction ($\alpha = .834$) and continuance intention ($\alpha = .905$)—indicating that the instrument was highly reliable for the present study. This step went beyond linguistic equivalence; it ensured the constructs were educationally relevant and culturally grounded, reflecting engagement dimensions meaningful to Malaysian learners within secondary textbook-based AR learning.

3.6 Data Collection Procedure

Data collection was conducted over two classroom sessions. The participating students were selected through cluster sampling, where one intact Form One class from the selected public secondary school was chosen, and all students who obtained parental consent were included in the study. In the first session, students used mobile devices to engage with the AR-enhanced textbook module under teacher supervision. In the second session, they completed the engagement questionnaire immediately after the learning activity.

This approach maintained ecological validity, as students interacted in a natural classroom environment, ensuring that responses reflected genuine engagement rather than laboratory-induced novelty effects. Participation was voluntary and data confidentiality was maintained throughout.

3.7 Data Analysis

3.7.1 *Exploratory Factor Analysis (EFA)*

Exploratory factor analysis (EFA) was used to investigate the fundamental factor structure and to verify the appropriate loading of items onto their designated constructions. The principal component analysis (PCA) extraction approach utilising Varimax rotation was implemented to optimise variance and facilitate factor understanding (Awang, 2015). The Kaiser-Meyer-Olkin (KMO) test evaluated sampling adequacy, whereas Bartlett's Test of Sphericity rated the data's appropriateness for factor analysis. A KMO value exceeding 0.80 and a significant Bartlett's test ($p < .05$) signified that the sample was adequate and the data were appropriate for exploratory factor analysis (Hair et al., 2010). Items with factor loadings under 0.50 were removed to guarantee construct integrity. The EFA results produced favourable values for all six components. Table 2 delineates the Kaiser-Meyer-Olkin values and the significance of the constructs:

Table 2: Kaiser Meyer Olkin Values and Construct Significance

Construct	KMO Measure of Sampling Adequacy	New Item Number	Bartlett's Test of Sphericity			Retained Item
			Approx. Chi Square	df	Sig.	
Visual Attraction	0.831	10	404.188	45	.000	10
Knowledge capability	0.829	7	161.348	21	.000	7
Situational Experience	0.832	8	279.621	28	.000	8
Attitude	0.824	9	405.118	36	.000	9
Satisfaction	0.854	7	272.058	21	.000	7
Intent to Continue Use	**0**.855	4	280.669	6	.000	4

All constructs exhibited satisfactory sampling adequacy (> .80) and significant correlations among items ($p < .05$), indicating that the dataset was suitable for factor analysis. The scree plot indicated a clear inflection at the sixth component, confirming a six-factor solution consistent with the theoretical model (see Table 3). Factor loadings above .60 were retained and all constructs demonstrated strong internal consistency (α = .783–.905). These results collectively demonstrated that the instrument has a stable factor structure and is both valid and reliable for measuring students' engagement in AR-based learning environments.

Table 3: Summary of Exploratory Factor Analysis Results

Construct	Factor Loadings Range	Cronbach's Alpha (α)	Theoretical Basis
Visual Attraction	0.62 – 0.83	0.801	CTML
Knowledge Capability	0.68 – 0.85	0.905	CTML
Situational Experience	0.63 – 0.82	0.783	CTML
Attitude	0.65 – 0.79	0.821	TCT
Satisfaction	0.67 – 0.84	0.889	TCT
Continuance Intention	0.70 – 0.86	0.873	TCT

All factor loadings exceeded the minimum threshold of 0.60, indicating strong construct validity and internal consistency across all dimensions. The results confirmed the six-factor model consistent with CTML (cognitive factors) and TCT (affective factors).

3.8 Reliability Analysis

Reliability testing was performed to evaluate the internal consistency of the items associated with each construct. Cronbach's alpha coefficients varied between 0.783 and 0.905, surpassing the acceptable threshold of 0.70 (McCowan et al., 1999). The findings demonstrated a high level of internal consistency and reliability throughout all constructs. Table 3 demonstrates that all constructs achieved Cronbach's alpha values exceeding 0.70, which signifies a strong level of internal consistency.

Table 3: Reliability Analysis of Constructs

Construct	Cronbach's Alpha	Reliability Level
Visual Attraction	0.830	High
Knowledge Capability	0.783	High
Situational Experience	0.804	High
Attitude	0.824	High
Satisfaction	0.834	High
Continuous Intention	0.905	Excellent

No items were found to significantly reduce the reliability of their respective constructs; hence, all were retained for the main study.

3.9 Ethical Considerations

This methodological design ensured a balanced integration of theoretical grounding, empirical validation and pedagogical authenticity. By situating the study within a real classroom and connecting CTML's cognitive processing with TCT's affective engagement, the research provided a robust framework for evaluating how AR-enhanced textbooks foster sustained learning interest. The methodology thus bridges the gap between instrument validation and practical educational innovation, contributing to both theory and classroom practice.

4. Results and Discussion

4.1 Overview of Findings

The exploratory factor analysis (EFA) confirmed a six-factor structure aligned with the theoretical frameworks of the cognitive theory of multimedia learning (CTML) and the technology continuance theory (TCT). The chosen constructs — visual attraction, knowledge capability, situational experience, attitude, satisfaction and continuance intention, demonstrated strong reliability, as indicated by Cronbach's alpha values between .783 and .905, surpassing the widely recognised threshold of .70 for internal consistency (Hair et al., 2010; Kline, 2015). The Kaiser–Meyer–Olkin (KMO) value of .812, along with a significant Bartlett's test of sphericity ($p < .001$), confirmed the sampling adequacy and the suitability of the data for factor analysis (Kogan et al., 2024). The psychometric results indicate that the instrument is both statistically valid and theoretically consistent for assessing engagement in AR-based learning environments.

All factor loadings exceeded 0.60, validating the internal consistency of the instrument. These statistical results provided empirical support for the conceptual model that links cognitive efficiency (CTML) and affective motivation (TCT) within AR-based textbook learning. However, beyond statistical strength, the analysis offered pedagogical insight into how students cognitively and emotionally interact with AR-enhanced learning materials. This approach is consistent with Sprock's (2020) assertion that immersive technologies, including the metaverse and AR, should be organised according to pedagogical strategies that promote higher-order thinking and collaborative learning. This study enhanced practical teaching design by linking validated theoretical constructs to classroom applications.

4.2 Cognitive Engagement: A CTML Perspective

The constructs of visual attraction, knowledge capability and situational experience embodied the cognitive dimension of engagement as delineated in CTML. The robust factor loadings for these categories suggested that students regarded AR features as intellectually engaging and conducive to comprehension. Augmented reality visual components, including three-dimensional images and animated demonstrations, efficiently garnered attention, facilitating enhanced cognitive engagement with educational material.

This discovery corroborates Mayer's (2008) claim that significant learning transpires when verbal and visual modalities are well-integrated. The AR-enhanced textbook environment alleviated cognitive overload by conveying abstract material via spatial and interactive representations. Students said that the capacity to visualise concepts in three-dimensional form facilitated their connection of academic ideas to real-world circumstances, exemplifying the dual-channel processing principle of CTML.

The high factor loadings for Knowledge Capability (0.68–0.85) indicate that students consistently perceived AR activities as enabling deeper understanding and self-directed learning. This outcome aligns with the principles of the cognitive theory of multimedia learning (CTML), which posits that well-designed multimedia supports cognitive processing and meaningful learning by integrating verbal and visual channels (Mayer, 2008). In addition, this finding resonates with contemporary research on AR in education showing that immersive and interactive AR environments foster learner autonomy, motivation and self-paced exploration (e.g., Ciloglu & Ustun, 2023; Karelkhan & Uderbayeva, 2024).

Such autonomy aligns with 21st-century educational goals that emphasised self-regulated learning, digital literacy and learners’ capacity to manage their own learning process (Norazah & Helmi, 2018). Therefore, AR-enhanced textbooks not only improve comprehension but also support cognitive autonomy, making them valuable tools for future-oriented pedagogy.

4.3 Affective Engagement: A TCT Perspective

The constructs of attitude, satisfaction and continuance intention encapsulated the affective and motivational aspects of engagement. Satisfaction exhibited a high reliability coefficient (α = .889), indicating that students' emotional responses to AR learning were predominantly positive. The participants reported the experience as enjoyable, rewarding and personally meaningful. These results are consistent with previous studies demonstrating that AR-based learning environments enhance students' affective engagement by increasing enjoyment, curiosity and perceived usefulness (Chen et al., 2021; Shyr et al., 2024).

From a theoretical standpoint, the strong association between satisfaction and continuance intention aligns with the core propositions of the technology continuance theory (TCT), which posits that learners are more likely to continue using a technology when it elicits positive emotional responses and fulfils learning expectations (Liao et al., 2009). Thus, the high satisfaction scores observed in this study corroborate contemporary findings that immersive AR experiences contribute not only to improved learning outcomes but also to sustained motivation and future usage intentions—key indicators of meaningful technology integration in modern education.

This finding supported the principle of TCT which posits that emotional fulfilment and positive attitudes are key determinants of technology continuance (Liao et al., 2009). In this study, student satisfaction was positively correlated with sustained engagement and the development of favourable attitudes towards learning with technology, indicating that students who found the AR activities enjoyable and personally meaningful were more inclined to continue using them. This trend echoes the findings of Chen et al. (2021), who reported that satisfaction significantly predicted students' intention to reuse AR-based learning tools.

Similarly, Kabir and Kang (2024) found that immersive AR environments enhanced learners' attitudes by increasing perceived usefulness and enjoyment, which subsequently strengthened continuance intention. The strong reliability of the Attitude measure (α = .821) further indicates that learners consistently perceived AR-enhanced textbook activities as advantageous and user-friendly, reinforcing contemporary arguments that affective responses are central drivers of sustained technology adoption in educational contexts. Collectively, these results confirm that affective constructs—particularly satisfaction and attitude—play a pivotal role in shaping technology continuance behaviours, thereby validating the theoretical assumptions of TCT within the context of AR learning environments.

The construct of continuance intention (α = .873) indicated that satisfaction correlated with the behavioural intention to reuse augmented reality in future learning contexts. This outcome has significant pedagogical implications: positive emotional experiences can enhance students' motivation to participate in self-directed and technology-assisted learning outside of the classroom.

4.4 Integrating Cognitive and Affective Dimensions

A dual-theoretical approach highlights the interaction between cognitive and affective dimensions in AR-based learning. Visual attraction serves as a cognitive stimulus through the use of interactive visual-verbal design, which, as outlined in the cognitive theory of multimedia learning (Mayer, 2008), enhances processing and comprehension. Simultaneously, learner satisfaction indicates an effective response and is significantly correlated with sustained engagement and technology continuance, as suggested by technology continuance theory (Liao et al., 2009). Empirical studies substantiate this interaction: Bacca et al. (2014) demonstrated that the interactive visual features of augmented reality (AR) significantly enhance student motivation, engagement and perceived usefulness. Additionally, Ibáñez and Delgado-Kloos (2018) and Chen et al. (2021) reported increased satisfaction and intention to reuse AR tools following AR-based instruction. The findings collectively support the outcomes of the current study and strengthen the idea that augmented reality learning environments, through the management of cognitive load and emotional engagement, can facilitate deeper understanding and promote sustained usage.

This interaction corresponds with recent educational research emphasising the importance of effective learning design to engage cognitive and emotional aspects. Research indicates that effectively designed augmented reality (AR) activities can elucidate complex concepts and enhance comprehension, especially when abstract material is represented through interactive media (Amores et al., 2022; Saat et al., 2021). AR environments have been shown to enhance curiosity and intrinsic motivation by offering enjoyable and immersive learning experiences (Ekanayake & Gayanika, 2022). Adhering to CTML principles, AR effectively mitigates cognitive overload by harmonising visual and verbal information (Buchner et al., 2021; Mayer, 2008). Additionally, the affective constructs outlined in TCT, including satisfaction and continuance intention, elucidate how personally meaningful and enjoyable experiences promote sustained engagement with the technology (Liao et al., 2009).

The verified six-factor approach offers educators a comprehensive foundation for creating AR-based learning experiences that are intellectually robust and emotionally captivating. This comprehensive understanding of engagement transcends mere statistical validation to provide actionable suggestions for classroom implementation.

4.5 Pedagogical Implications

The results of this study have significant educational implications for educators, curriculum developers and legislators aiming to incorporate augmented reality (AR) into classroom teaching. The findings emphasised that successful AR-based textbook learning necessitates a careful equilibrium between cognitive lucidity and emotional involvement. When constructed in accordance with CTML principles, AR elements can enhance comprehension by converting abstract knowledge into concrete, visual experiences that alleviate cognitive strain. The affective factor highlighted in TCT indicates that student happiness and enjoyment are essential for maintaining motivation and promoting long-term involvement.

Educators can utilise these data to create augmented reality learning experiences that are engaging, visually orientated and connected with educational objectives.

Educators should integrate augmented reality meaningfully into instructional sequences to reinforce essential concepts and foster self-directed learning, rather than perceiving it as a novelty or extra tool. The validated constructs revealed in this study can function as pedagogical indicators to inform classroom practice, assisting educators in monitoring students' cognitive engagement, emotional responses and preparedness for continued learning through technology.

From a curricular standpoint, AR integration can augment textbook interaction, converting static content into multimodal resources that accommodate varied learning preferences. Curriculum creators can utilise the validated scale to assess engagement and guide the iterative design of AR-enhanced courses. Ultimately, these data confirmed that significant technology integration is not aimed at supplanting traditional pedagogy but at enhancing it—fostering learning experiences that are cognitively successful, emotionally fulfilling and pedagogically robust.

4.6 Implications for Practice and Research

The validated instrument serves as a useful resource for researchers, educators and policymakers by identifying essential cognitive and motivational factors such as visual appeal and user satisfaction—that influence the use of augmented reality (AR) in learning environments. This framework offers researchers a dependable method for examining these factors through structural equation modelling (SEM), while simultaneously guiding the design of AR-based educational materials that enhance both cognitive processing and affective engagement. The positive indicators of students' readiness and engagement further suggest that AR can be effectively integrated into core subjects, including science, geography and history, where spatial and visual representations improve understanding. These results also provide policymakers with clear direction for developing professional development programmed that equip teachers to integrated AR pedagogically, ensuring that AR adoption moves beyond technical implementation towards meaningful instructional practice.

In summary, the pilot study demonstrated that the modified AR-based learning tool is valid, dependable and appropriately suited for Malaysian secondary school students. The six validated constructs create a unified measurement model that encompasses both cognitive and emotional aspects of augmented reality learning experiences. The empirical alignment with CTML and TCT enhances the instrument's theoretical foundation, rendering it appropriate for use in upcoming large-scale studies. The validated instrument contributes to both methodological advancements in educational technology studies and the practical aim of improving students' digital learning readiness and motivation through the integration of immersive technologies.

Overall, the validated instrument serves as a practical reference for researchers, educators and policymakers by delineating the cognitive and affective factors essential for the integration of augmented reality in classroom learning. The framework provides guidance for designing AR-based materials that improve comprehension via visualisation and maintain motivation through emotionally significant learning experiences. The positive indicators of student readiness and engagement indicate that augmented reality can be effectively integrated into core subjects, including science, geography and history, where spatial and visual representations enhance conceptual understanding. The insights delineate a clear framework for the development of professional development programs aimed at enabling teachers to use augmented reality pedagogically, rather than solely from a technological perspective, thereby ensuring that AR implementation fosters meaningful instructional enhancement.

5. Conclusion

5.1 Conclusion

This research examined student engagement in augmented reality (AR)-enhanced textbook learning by developing and validating a six-construct cognitive-affective framework. Utilising the cognitive theory of multimedia learning (CTML) and the technology continuance theory (TCT), the study established that both cognitive and affective dimensions are essential for comprehending students' ongoing intention to engage with augmented reality in their learning processes. The validated constructs—visual attraction, knowledge capability, situational experience, attitude, satisfaction and continuance intention—exhibited strong reliability and theoretical coherence, thereby affirming the appropriateness of this framework for analysing engagement in technology-supported learning environments.

The findings indicated that effective augmented reality learning requires a balance between cognitive efficiency and emotional satisfaction. From the perspective of CTMLAR facilitates learning by improving cognitive processing via multimodal visualisation and interaction, thereby aiding students in converting abstract concepts into meaningful understanding. From the TCT perspective, students' positive attitudes, enjoyment and satisfaction significantly influenced their willingness to continue utilising AR after initial exposure. These insights confirmed that meaningful engagement arises when the integration of technology is aligned with cognitive and affective learning processes.

The study provides a validated framework for educators and curriculum designers to evaluate and improve student engagement in AR-enhanced textbooks and comparable digital learning environments. The framework functions as both a psychometric instrument and a pedagogical model, connecting theory, practice and classroom application. Educators may utilise the identified constructs as effective indicators for lesson design aimed at promoting curiosity, comprehension and enduring motivation. The model can inform the creation of interactive materials at the curriculum level, enhancing traditional textbooks by incorporating visual, experiential and affective aspects of learning.

Overall, this study enhances existing scholarship by illustrating how a theoretically informed framework can facilitate the intentional application of immersive technologies in secondary education. The research demonstrates the pedagogical value of augmented reality, moving beyond its novelty by illustrating how clearly defined cognitive and affective indicators can facilitate the planning, evaluation and refinement of technology-enhanced learning. This study provides a validated measurement tool and a structured framework for instructional decision-making, thereby promoting a principled and evidence-based approach to the integration of emerging technologies in educational settings. Future research could extend this framework to various subjects, cultural contexts and technological environments to assess its broader applicability and enduring influence on learning conduct.

6. Conflict of Interest

The author declares that there are no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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