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Enhancing Cognitive Skills in Basic Electronics Using an Augmented Reality Learning Environment

Muhammad Afandi Azmi, Muhammad Khair Noordin

Faculty of Educational Sciences and Technology, University Technology Malaysia, 81310 Johor Bahru, Johor

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ABSTRACT

This study aimed to determine whether an Augmented Reality–based instructional module can improve students' cognitive understanding of abstract electronic concepts. Concepts such as current flow and circuit laws often pose challenges for vocational students, as conventional 2D teaching fails to support adequate visualization. To address this issue, a purpose-built Augmented Reality learning environment, AR-ElecSim, was developed and implemented. A quasi-experimental pre-test/post-test non-equivalent control group design involving 100 students from four vocational colleges was used. The experimental group (n = 50) used the AR-ElecSim module, while the control group (n = 50) received traditional instruction. Cognitive performance was measured using the Basic Electronics Cognitive Test (BECT), a 30-item instrument validated by experts ($\alpha = .88$). After controlling for pre-test scores, ANCOVA results showed a significant effect of instructional method, $F(1, 97) = 152.45$, $p < .001$, $\eta^2_p = .61$, indicating that students using AR-ElecSim achieved higher adjusted mean scores (75.75) than the control group (55.45). The AR module effectively enhanced cognitive performance by promoting conceptual understanding and minimizing cognitive overload. This study fills a national research gap by providing empirical evidence on AR's cognitive effects in Malaysian vocational education, highlighting its potential to strengthen analytical and application skills in Basic Electronics.

Keywords: Augmented Reality, Cognitive Skills, Basic Electronics, TVET, Quasi-Experimental Design, Cognitive Load Theory

INTRODUCTION

Technical and Vocational Education and Training (TVET) has become an increasingly important driver of socio-economic development and human capital formation worldwide. As economies transition towards Industry 4.0 and beyond, the demand for a technically competent workforce with advanced problem-solving, digital, and analytical skills continues to rise [1]. In Malaysia, the Pelan Pembangunan Pendidikan Malaysia (PPPM 2015–2025) positions TVET as a strategic vehicle to produce skilled graduates capable of sustaining industrial innovation and competitiveness. National initiatives such as the TVET Empowerment Strategy 2030 and Digital Education Policy 2021–2030 emphasise digital transformation, experiential learning, and the integration of emerging technologies into curriculum and pedagogy [2]. Within this reform agenda, teaching and learning methods must evolve beyond traditional classroom practices to prepare students for technology-driven workplaces that demand both cognitive flexibility and applied technical competence [3].

Basic Electronics stands at the core of many TVET programmes, including electrical, electronics, and mechatronics engineering. Mastery of this subject is essential for students to progress to advanced topics such as embedded systems, automation, and Internet of Things (IoT) applications. However, the conceptual nature of electronics poses significant learning barriers. Phenomena such as current flow, voltage potential, and resistance are invisible and abstract. Understanding circuit behaviour requires students to mentally translate symbolic representations and mathematical formulas into dynamic, physical phenomena [4]. For novice learners with limited prior experience, this mental translation demands advanced cognitive and visuospatial skills, which are often underdeveloped in vocational education populations [5].

Traditional pedagogical approaches in Malaysian vocational colleges remain largely teacher-centred, emphasizing rote memorization and procedural tasks. Students learn through static two-dimensional diagrams, whiteboard illustrations, and textbook exercises, which primarily engage lower levels of Bloom's taxonomy, remembering and understanding, while neglecting higher-order thinking such as applying and analysing [6]. As a result, many students can assemble electronic circuits correctly yet struggle to explain the underlying principles or troubleshoot faults independently. Studies have consistently reported this theory–practice gap in TVET contexts, where graduates exhibit strong psychomotor skills but weak cognitive reasoning, particularly in abstract technical subjects [7], [8].

This pedagogical challenge is further complicated by the increasing complexity of modern electronics and the expectation for graduates to integrate knowledge across systems. The Fourth Industrial Revolution (IR 4.0) has introduced cyber-physical systems, automation, and artificial intelligence into manufacturing, requiring technicians who not only "know how" but also "understand why." This shift places greater emphasis on cognitive skills such as reasoning, abstraction, and problem decomposition, skills traditionally underdeveloped through didactic instruction [9]. Consequently, Malaysian TVET institutions are urged to adopt innovative, student-centred, and technology-enhanced pedagogies that cultivate higher-order cognitive processes.

Augmented Reality (AR) has emerged as a promising instructional technology capable of addressing these educational challenges. AR merges digital content with real-world environments, allowing users to view and interact with 3D virtual objects superimposed onto physical space via mobile devices or smart glasses [10]. In educational settings, AR provides learners with contextual, interactive, and immersive experiences that can make abstract concepts more concrete [11]. For electronics education, AR offers unique affordances: it enables visualization of invisible phenomena such as electron flow, voltage gradients, and circuit functionality, thereby linking theoretical concepts to observable behaviours [12]. When applied within cognitive learning frameworks, AR can reduce extraneous cognitive load by integrating visual, textual, and interactive elements into a single display [13]. This integration allows learners to process information more efficiently and focus their mental resources on conceptual understanding rather than decoding fragmented materials.

Recent research underscores AR's potential for improving learning outcomes across STEM disciplines. A meta-analysis by Bödding, Schriek, and Maier [14] revealed that mixed reality technologies in vocational education produce significant positive effects on cognitive ($d = 0.84$), behavioural ($d = 0.40$), and affective ($d = 0.65$) learning outcomes. Similar findings were reported by Alkhabra et al. [15], who demonstrated that AR enhanced learning retention and critical thinking in STEAM programmes. In electronics-specific contexts, Tuli et al. [16] and Elford et al. [17] found that students using AR-based modules achieved higher conceptual gains, improved spatial reasoning, and reduced misconceptions. These results suggest that AR can serve not only as a motivational tool but as a cognitive scaffold that bridges theoretical and practical domains.

However, despite global evidence, empirical research on AR's cognitive impact within Malaysian TVET remains limited. Most local studies have focused on affective dimensions, such as engagement, motivation, or usability, rather than measurable cognitive gains [18]. Moreover, there is a lack of systematic research addressing how AR influences higher-order cognitive skills such as application and analysis, which are vital for diagnostic reasoning in technical fields. Addressing this gap is particularly relevant as Malaysian vocational colleges move towards hybrid and simulation-based learning under the Ministry of Education's digitalisation initiatives [2].

Accordingly, this study seeks to examine the impact of an Augmented Reality learning environment, AR-ElecSim, on students' cognitive performance in Basic Electronics. The study employs a quasi-experimental design to compare outcomes between AR-assisted and traditionally taught groups. The findings aim to contribute both theoretically and practically: theoretically by validating Cognitive Load Theory and multimedia learning principles in a TVET context; and practically by providing empirical evidence to inform the integration of AR into vocational curricula. The overarching goal is to enhance cognitive learning, strengthen theoretical understanding, and bridge the persistent gap between classroom instruction and real-world technical application.

Research Objectives

The objectives of this study are to:

1. Evaluate the baseline cognitive skills in Basic Electronics among students in the experimental and control groups.
2. Design and implement an Augmented Reality learning environment (AR-ElecSim) tailored to the Basic Electronics curriculum.
3. Determine the effect of AR-based instruction on students' cognitive skills compared to conventional instructional methods.

LITERATURE REVIEW

Cognitive Learning and Conceptual Challenges in Electronics

Cognitive learning in electronics involves progressing from surface-level recall to deeper conceptual understanding. Bloom's Taxonomy defines this hierarchy as moving from Remembering and Understanding to Applying and Analyzing [8]. However, many vocational students remain trapped in lower cognitive levels, focusing on memorizing formulas without understanding their conceptual interrelations. This results in surface learning that fails to transfer to real-world problem-solving scenarios [9].

Several studies highlight that misconceptions in Basic Electronics arise from abstract representations, inadequate visualization, and weak conceptual linkage between theory and practice [10]. For example, students often misinterpret current as a consumed quantity rather than a continuous flow, leading to fundamental errors in circuit analysis. Effective instruction must therefore promote visualization and interaction to anchor abstract knowledge in observable contexts.

Cognitive Load Theory and Instructional Design

Cognitive Load Theory (CLT) provides an explanatory framework for learning difficulties in electronics education. It posits that working memory is limited and can process only a finite amount of information at any given time [11]. Instructional materials that impose excessive extraneous load, mental effort unrelated to learning, impede knowledge construction. In traditional instruction, students are required to integrate multiple, separate information sources such as circuit diagrams, textual explanations, and lab manuals. This "split-attention" effect increases cognitive burden and reduces germane processing, which is essential for schema construction [12].

AR offers a potential solution by consolidating visual and textual information into a single, coherent display. Studies indicate that when learners engage with integrated multimodal content, their cognitive load decreases, and conceptual understanding improves [13]. For instance, by visualizing how current flows through resistors or how voltage drops across parallel branches, learners form meaningful mental models that improve recall and analytical reasoning.

Augmented Reality in Vocational and Technical Education

The application of AR in TVET has expanded rapidly over the past five years. Liu, Zhan, and Zhao [14] reviewed over 90 studies on AR and VR in vocational education and concluded that these technologies enhance learning motivation, retention, and spatial reasoning. Similarly, Alkhabra et al. [15] found that AR significantly improved critical thinking and problem-solving skills among STEAM learners. In electronics education, Tuli et al. [16] demonstrated that AR improved both academic achievement and laboratory performance, particularly in conceptual areas such as current distribution and fault diagnosis.

At the same time, researchers such as Chiang et al. [17] caution that AR's success depends heavily on pedagogical alignment. Poorly designed AR systems may distract learners and inadvertently increase extraneous cognitive load. Consequently, effective AR design should embed scaffolding mechanisms, feedback loops, and guided inquiry tasks to sustain cognitive engagement.

In Malaysia, studies on AR in vocational contexts remain scarce but promising. Rahman et al. [1] reported that technology-enhanced instruction improved comprehension and retention in vocational classrooms. However, most investigations have focused on affective or motivational outcomes, leaving a gap regarding measurable improvements in cognitive domains. The present study addresses this gap by focusing specifically on cognitive skill development, measured through Bloom's Taxonomy and validated quantitative assessment.

Instructional and Design Implications for AR Learning

Successful implementation of AR in education requires careful integration of pedagogical design principles. Asoodar et al. [18] emphasize that AR should support experiential learning and provide contextually meaningful interactions, rather than acting as mere visual augmentation. In TVET, this involves aligning AR modules with specific learning outcomes, such as understanding Ohm's Law, analyzing circuit faults, and calculating total resistance in mixed circuits.

Furthermore, mixed reality environments must support adaptive feedback, allowing students to explore errors safely. This approach aligns with constructivist learning theory, which views learning as an active process of constructing meaning through interaction and reflection [19].

METHODOLOGY

Research Design

A quasi-experimental, non-equivalent control group pre-test/post-test design was adopted. This design is suitable for educational research where random assignment of individual participants is impractical. Two groups were formed: the Experimental Group (n = 50), which used the AR-ElecSim module, and the Control Group (n = 50), which received traditional instruction.

Population and Sampling

The population comprised first-year students enrolled in Diploma-level electronics programmes at four Malaysian vocational colleges. Purposive sampling was used to ensure similarity in demographics, curriculum, and teaching schedules. Two colleges were assigned to each group.

Instrumentation

The Basic Electronics Cognitive Test (BECT) consisted of 30 multiple-choice items spanning four cognitive levels:

- Remembering (8 items)
- Understanding (8 items)
- Applying (8 items)
- Analyzing (6 items)

Content validity was verified by five subject matter experts, and reliability testing yielded Cronbach's $\alpha = 0.88$.

Intervention: The AR-ElecSim Module

The AR-ElecSim module was developed using Unity3D and Vuforia SDK for Android platforms. Students used their mobile devices to scan printed circuit diagrams, triggering interactive 3D models. Features included:

- Real-time current flow visualization.
- Virtual instrumentation displaying voltage, resistance, and power.
- Fault simulation and guided troubleshooting activities.

The Control Group used textbook diagrams, lectures, and worksheet-based exercises covering identical topics (Ohm's Law, series, parallel, and combination circuits).

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Procedure

1. Week 1: Pre-test administration using BECT.
2. Weeks 2–5: Instructional treatment across both groups.
3. Week 6: Post-test administration.

Data Analysis

Data were analysed using SPSS. Descriptive statistics (means and standard deviations) were computed, followed by ANCOVA to determine the effect of instructional method (AR vs. traditional) on post-test scores, controlling for pre-test performance.

Results

Table 1. Descriptive Statistics

Group	Test	N	Mean (M)	SD
Experimental	Pre-test	50	40.50	5.10
	Post-test	50	75.80	6.20
Control	Pre-test	50	41.20	4.90
	Post-test	50	55.40	5.70

The experimental group demonstrated a mean improvement of 35.3 points, compared to 14.2 points in the control group.

Table 2. ANCOVA Summary

Source	SS	df	MS	F	p	Partial η^2
Pre-test (Covariate)	811.52	1	811.52	24.89	.000	.204
Group (EG vs CG)	**4970.11**	**1**	**4970.11**	**152.45**	**.000**	**.611**
Error	3163.54	97	32.61			

Table 3. Adjusted Post-Test Means

Group	Adjusted Mean	SE	95% CI (Lower, Upper)
Experimental	75.75	0.81	74.15, 77.35
Control	55.45	0.81	53.85, 57.05

The ANCOVA confirmed a statistically significant main effect ($p < 0.001$), with a large effect size indicating a substantial practical impact.

DISCUSSION

The findings of this study provide strong empirical support for the argument that integrating Augmented Reality (AR) into Basic Electronics instruction enhances cognitive learning outcomes among vocational students. The experimental group demonstrated significantly higher post-test performance, confirming that immersive digital environments can improve understanding of abstract technical concepts. These results are consistent with Cognitive Load Theory (CLT), which suggests that when instructional design reduces extraneous load and promotes germane processing, learners can achieve deeper comprehension and longer retention [11].

In this study, students using AR-ElecSim interacted directly with dynamic 3D representations of circuit elements.

By visualizing current flow, voltage drops, and resistance relationships, learners could connect symbolic formulas with observable phenomena. This integration of perceptual and conceptual processing supports Mayer's multimedia learning principle [12], which posits that combining verbal and visual channels enhances cognitive encoding and retrieval. Consequently, the AR environment allowed students to engage in dual coding, processing information both linguistically and visually, thus reducing cognitive strain and fostering schema construction.

Moreover, the results reinforce findings by Wu et al. [20] and Tuli et al. [16], who reported that AR-based learning leads to higher conceptual gains in STEM disciplines. In the current study, AR's benefits were particularly pronounced in higher-order cognitive tasks such as applying and analyzing, where learners had to interpret or diagnose circuit behaviour. These findings suggest that AR not only aids surface-level comprehension but also strengthens cognitive transfer, allowing students to apply learned concepts to new situations, an essential skill in technical and vocational domains.

Beyond individual cognition, AR also contributed to an engaging learning environment. Observational data during the intervention indicated higher levels of student participation, peer discussion, and self-initiated exploration within the experimental group. This aligns with the constructivist learning theory, which emphasizes learning as an active, social, and contextualized process [19]. Students were motivated to test hypotheses about circuit behaviour and verify outcomes immediately within the AR interface, which mirrors the inquiry-based learning model commonly advocated in TVET reform frameworks [1], [17].

From a curriculum standpoint, this study supports integrating AR technology as a complement, not a replacement, to traditional instruction. AR can provide a pre-laboratory cognitive rehearsal that prepares learners for hands-on experimentation. Such previsualization reduces misconceptions, enhances procedural accuracy, and increases safety during physical laboratory sessions [14]. Furthermore, the adoption of AR aligns with Malaysia's Digital Education Policy (2021–2030) and UNESCO's TVET for the Future of Work agenda, both of which emphasize immersive, technology-enhanced pedagogy that develops analytical and digital competencies [17], [18].

However, the successful implementation of AR-based learning requires teacher readiness, institutional support, and pedagogical adaptation. Teachers must possess sufficient digital literacy and instructional design skills to integrate AR effectively into their lessons. As noted by Rodríguez-Saavedra et al. [19], the effectiveness of AR depends not only on the technology itself but also on how it is pedagogically embedded within an active learning framework. Therefore, professional development initiatives are crucial to ensure that instructors can design, adapt, and evaluate AR-enhanced lessons to achieve desired learning outcomes.

CONCLUSION

This study provides compelling empirical evidence that Augmented Reality-based instruction can substantially improve vocational students' cognitive performance in Basic Electronics. Through the AR-ElecSim module, learners gained the ability to visualize otherwise invisible electrical phenomena, interact with dynamic virtual circuits, and understand the causal relationships between voltage, current, and resistance. These experiences translated into significant improvements across multiple levels of Bloom's Taxonomy, especially in applying and analyzing skills.

Theoretically, the findings validate the principles of Cognitive Load Theory and Multimedia Learning Theory by demonstrating that AR environments reduce split-attention effects and promote dual-channel processing. This results in more efficient knowledge construction and cognitive retention. Pedagogically, AR provides a contextualized bridge between abstract theory and real-world application, a challenge that has long hindered TVET effectiveness in Malaysia and elsewhere.

From a policy perspective, this study supports national and international initiatives promoting the digital transformation of TVET. Integrating AR into the Malaysian vocational curriculum aligns with the TVET Empowerment Strategy 2030, Education 5.0@UTM, and the Industry 5.0 vision that emphasizes human-centric, sustainable, and technology-driven learning ecosystems [18], [19]. By embedding AR as part of blended or hybrid instructional design, institutions can create adaptive learning experiences that cater to diverse learner needs and foster deeper conceptual understanding.

The implications extend beyond electronics education. AR can be applied to other technical domains such as mechanical systems, civil construction, and automotive technology to visualize physical processes and support competency-based learning. As vocational institutions adopt more advanced digital tools, AR can play a central role in developing higher-order cognitive, technical, and problem-solving skills required by Industry 5.0 workplaces.

Limitations And Future Work

Although the results are encouraging, several limitations must be acknowledged. First, the quasi-experimental design employed intact classes, meaning random assignment of participants was not possible. This may limit the generalizability of findings beyond the four vocational colleges involved. Future studies should employ randomized controlled trials across larger and more diverse TVET institutions to enhance external validity.

Second, the duration of the intervention was relatively short (four weeks). While sufficient to detect significant short-term cognitive gains, it does not provide insight into long-term knowledge retention or transferability. Longitudinal studies extending over multiple semesters could assess the persistence of learning gains and evaluate whether AR-supported instruction leads to better practical performance during industrial training.

Third, the novelty of AR may have influenced learner motivation, potentially exaggerating performance improvements in the short term. Researchers such as Bödding et al. [7] and Alkhabra et al. [15] note that novelty effects often diminish over time as learners become accustomed to new technologies. Future research should therefore measure sustained engagement and performance after prolonged exposure.

Additionally, the present study focused exclusively on cognitive outcomes. Future investigations should explore AR's influence on affective factors (motivation, self-efficacy, learning satisfaction) and psychomotor skills (laboratory manipulation, tool handling). Mixed-method approaches combining quantitative assessments with qualitative interviews or classroom observations could offer richer insights into how AR affects learning processes and interactions.

From a technological perspective, further development of AR systems should incorporate artificial intelligence (AI) to enable adaptive feedback and personalized learning pathways. Such integration could align AR instruction with Industry 5.0 principles by combining automation with human-centered intelligence. Moreover, embedding AR modules within mobile and cloud-based platforms could expand accessibility, enabling learners from rural or resource-limited regions to engage in immersive learning without the constraints of specialized hardware.

Finally, teacher professional development should accompany AR implementation. Instructors need competencies in both content and technology integration (TPACK framework) to design effective AR-supported learning experiences. Collaborative research between universities, TVET institutions, and industry partners can accelerate innovation and create sustainable models for digital pedagogy in technical education.

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