Factors Influencing Students' Critical Thinking Disposition in Case-Based Method Learning

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***Abstract*—Previous research has predominantly examined the effectiveness of learning applications through experimental designs, yet few have explored how these technologies shape students' internal cognitive and psychological skills. This study makes a novel contribution by embedding a smart learning application within an integrated psychological-cognitive framework, i.e., prior knowledge, metacognition, cognitive engagement, and self-regulated learning, to explain the development of critical thinking disposition. The learning process was designed using the case method, involving 369 undergraduates in the Faculty of Engineering at Universitas Negeri Padang, Indonesia. Data were collected via an online survey and analyzed through Structural Equation Modeling (SEM) with SmartPLS 3 and Fuzzy C-Means Clustering (FCM) with JASP. Results of the direct effect analysis show that prior knowledge and metacognitive do not directly influence critical thinking, while cognitive engagement and self-regulated learning exert significant positive effects. Indirect effect analysis further indicates that prior knowledge and metacognitive significantly affect critical thinking when mediated by cognitive engagement and self-regulated learning. Clustering analysis reveals that most respondents engage with the application at a moderate level. Therefore, targeted interventions such as scaffolding strategies to guide learning processes, adaptive feedback to foster metacognitive monitoring, and gamification elements to sustain motivation are essential for enhancing engagement, reducing passive use, and maximizing the educational impact of smart learning technologies.**

***Keywords*—critical thinking disposition, case-based method, smart learning application, Structural Equation Modeling (SEM), Fuzzy C-Means Clustering (FCM)**

I. Introduction

The Sustainable Development Goals (SDGs) constitute a global blueprint and joint action agenda designed to promote the well-being of current and future generations. Of the 17 goals outlined in the SDGs, one specifically targets the education sector, focusing on the goal of providing inclusive and equitable quality education for all. In this context, quality education is defined by the adoption of active and inclusive learning practices.

Integrating technology into education is a fundamental strategy for advancing active learning. Numerous studies worldwide have demonstrated that innovative systems and digital tools enable instructors to enhance students' comprehension of course content [1–3]. A notable development in contemporary education is the implementation of Android-based learning applications [4, 5]. Nowadays, smartphones are no longer used solely for communication. Instead, they have become valuable instructional tools. One practical example is case-based learning, in which students engage with real-world scenarios that foster critical thinking and problem-solving abilities [6, 7]. However, students' success in addressing these cases is determined not only by the technology employed but also by internal factors such as prior knowledge [8], metacognition [9], cognitive engagement [10], and self-regulated learning [11]. In this sense, technology functions merely as a facilitator, while students' internal competencies remain the primary drivers of meaningful learning outcomes.

In general, the use of learning applications in education has become a major focus of research worldwide. However, most international studies still concentrate on measuring the effectiveness of such applications through experimental designs [12–14]. Empirical research examining how students' psychological and cognitive factors develop in conjunction with the use of learning applications remains scarce. As a result, the literature offers a limited understanding of how these technologies foster internal learning skills, particularly within the educational context.

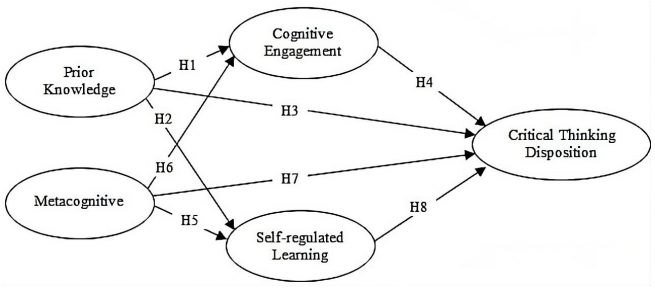

Fig. 1. Research framework.

This study was conducted in the context of vocational higher education in Indonesia. The findings are expected to provide practical implications for strengthening national learning strategies through the effective use of smart learning application to enhance critical thinking disposition. At the same time, the issues addressed in this study are not limited to the local context. The limited evidence on how students' psychological and cognitive factors evolve with the use of learning applications also represents a gap in the international literature. Therefore, the purpose of this study is to investigate the role of smart learning application in enhancing critical

thinking disposition among students in vocational higher education. Special emphasis is placed on examining the interplay among prior knowledge, metacognition, cognitive engagement, and self-regulated learning. The research objectives are reflected in the conceptual framework illustrated in Fig. 1.

The conceptual framework underpinning this research posits eight direct hypotheses, which are formulated as follows:

H1: prior knowledge has a positive impact on cognitive engagement.

H2: prior knowledge has a positive impact on self-regulated learning.

H3: prior knowledge has a positive impact on critical thinking disposition.

H4: cognitive engagement has a positive impact on critical thinking disposition.

H5: metacognitive has a positive impact on self-regulated learning.

H6: metacognitive has a positive impact on cognitive engagement.

H7: metacognitive has a positive impact on critical thinking disposition.

H8: self-regulated learning has a positive impact on critical thinking disposition.

Furthermore, the model proposes four indirect hypotheses, which are formulated as follows:

H9: prior knowledge has a positive impact on critical thinking disposition through cognitive engagement.

H10: prior knowledge has a positive impact on critical thinking disposition through self-regulated learning.

H11: metacognitive has a positive impact on critical thinking disposition through self-regulated learning.

H12: metacognitive has a positive impact on critical thinking disposition through cognitive engagement.

The theoretical development of this research model is grounded in several pertinent strands of literature. Constructivist learning theory posits that students actively construct new knowledge upon the foundation of their prior understanding, which shapes the way they interpret, analyze, and integrate novel information. Robust prior knowledge has been shown to influence cognitive engagement directly [15]. Likewise, a strong foundation of prior knowledge fosters more effective self-regulation in learning [16]. Consequently, such knowledge is believed to equip students with the cognitive acumen necessary to process information with greater precision and depth. Furthermore, metacognitive theory posits that one's awareness and regulation of their own thinking processes shape cognitive engagement [17]. Additionally, self-regulated learning theory elucidates how metacognition drives purposeful planning, vigilant monitoring, and thoughtful self-reflection. Therefore, the ability to reason about one's own thinking significantly contributes to students' capacity for critical thinking.

All hypotheses in this model are crafted not merely to test the direct impact of each factor on critical thinking, but also to chart the intricate web of inter-variable linkages, including potential mediation pathways. The mediation analysis is conducted as the final stage, serving to sharpen and enrich the understanding of these relational dynamics.

II. Literature Review

A. Prior Knowledge

Prior knowledge refers to pre-existing cognitive structures that serve to interpret and make sense of new information. This concept was first introduced by Jean Piaget (1926) in the context of cognitive development, emphasizing how individuals connect various representations and phenomena through flexible mental schemas [18]. These schemas are formed through a series of life experiences and are typically general in nature, not focusing on the specific details of connections among units and subunits of information. In later developments, prior knowledge has been understood as the product of constructed conceptual schemas that influence how new information is processed, comprehended, and stored in memory [19]. Although prior knowledge was initially viewed as a repository and collection of information, current studies suggest that this ability has evolved into the analysis and synthesis of specific conditions. The resulting analysis indicates that an individual possesses critical thinking skills. However, some studies assert prior knowledge indicates a dual condition. An individual may be capable of evaluating information effectively, yet under certain circumstances, can become ensnared in interpretive bias due to excessive exposure to information [20]. Therefore, this condition harbors both positive and negative aspects depending on the context and the individual.

B. Metacognitive

The concept of metacognition traces back to John H. Flavell's pioneering work on children's ability to recognize what they know and do not know, as well as how they manage this knowledge to solve problems effectively [21]. Following Flavell's introduction of the term, numerous scholars have further developed the concept. Metacognition is now understood not only as awareness of one's own thinking processes but also as the ability to regulate strategies for learning, problem-solving, and critical thinking. In simple terms, metacognition refers to one's awareness and control over one's own cognitive processes [22]. It is often described as thinking about thinking. Individuals can monitor and direct their own thoughts and emotions. For example, someone employing metacognitive strategies may continually ask themselves reflective questions to guide their thinking,

'What am I doing working?'

'Can I do this?'

'How can I complete this work easily?'

'How can I do this in a different way next time?'

Strong metacognition is more capable of managing cognitive load, overcoming distractions, and achieving better learning outcomes [23]. However, several studies suggest that the ultimate impact of metacognition extends beyond learning outcomes, also to enhance critical thinking [24, 25]. Therefore, this relationship is both theoretically sound, particularly within the context of vocational higher education.

C. Cognitive Engagement

Cognitive engagement is driven by an individual's willingness to invest mental effort in thinking and reasoning. This skill is defined in accordance with Craik and Lockhart's (1972) levels of processing theory, which distinguishes between two types of cognitive engagement, i.e., deep

engagement and shallow engagement [26]. Deep engagement is characterized by more elaborate information processing, wherein new information is integrated with prior knowledge. In contrast, shallow engagement tends to be mechanical in nature, such as skimming text without fully comprehending its content. Cognitive engagement is also closely linked to mental effort, reflecting the extent to which an individual is willing to exert cognitive resources to complete a learning task. As time progresses, cognitive engagement has come to be understood as a form of cognitive investment. It reflects a student's commitment to understanding learning materials, including those delivered through technology [27]. This type of engagement does not merely measure how much cognitive effort students are willing to allocate, but also the quality of the information processing they perform. When cognitive engagement occurs sequentially, students do not merely receive information passively; instead, they connect it to their prior knowledge and evaluate its relevance, which helps them develop critical thinking.

D. Self-Regulated Learning

Self-regulated learning refers to an individual's capacity to control and manage their own learning strategies and behaviors in pursuit of academic goals [28]. Self-regulation process comprises three interrelated phases, i.e., (1) planning, which involves setting goals, selecting appropriate learning strategies, and developing an action plan to guide learning efforts, (2) monitoring, which entails tracking one's progress, understanding, and performance relative to established goals and standards, and (3) control and adaptation, which involves making adjustments or modifications to learning strategies, resources, or goals to optimize learning outcomes. Self-regulated learning is not a fixed trait but rather a dynamic skill that can be shaped, developed, and refined through deliberate practice and sustained effort.

Research suggests that self-regulated learning and critical thinking are closely interconnected [29]. Self-regulation cultivates internal discipline in students through the habitual practices of planning, monitoring, and evaluating their own learning, while critical thinking adds reflective depth to ensure the regulation process is meaningful and effective. These two competencies are mutually reinforcing, though empirical data is still needed to better understand their relationship within the context of learning application.

E. Critical Thinking Disposition

The concept of critical thinking can be traced back to the ideas of Socrates, who is renowned for the Socratic Method [30]. This perspective encouraged individuals of its time to broaden their horizons and critically examine prevailing beliefs, rather than unreflectively accepting claims advanced by those in positions of authority or influence [31]. However, efforts to cultivate a critical mindset often encounter resistance within social and educational domains. Those who interrogate entrenched assumptions or traditional perspectives are frequently regarded as disruptive. In the academic context, students who develop critical thinking do more than memorize information. Instead, they probe concepts, demand evidence, and scrutinize arguments. The novel insights generated through critical inquiry function as catalysts for innovation, scientific discovery, and societal advancement. In learning environments that promote intellectual openness, critically engaged students constitute a valuable resource by offering fresh perspectives on complex issues. They are not passive recipients of knowledge but active agents in advancing and enriching the field of study.

III. Materials and Methods

A. Research Design

This study employs a quantitative approach using an associative research design. Based on this design, the primary aim is to analyze the relationships among students' psychological and cognitive variables. This design was deliberately chosen to align with the learning method implemented, namely the case method [32, 33]. The case method positions students at the center of the learning process, guiding them to analyze, evaluate, and solve real-world problems relevant to the course material.

Fig. 2. Learning application display.

The case study underpinning this research centers on mastering foundational electrical principles, most notably Ohm's Law and Kirchhoff's Law, through their practical application in the construction of real-world electrical circuits. Throughout the instructional process, students were assisted by a smartphone-based learning tool titled Basic Laws of Electronics. This application, developed using a Case-Based Method (CBM) framework, integrates five key features, i.e., (1) Instructions, delivering sequential, step-by-step guidance that enables learners to map their study trajectory, thereby cultivating metacognitive planning strategically. (2) Competencies, clearly articulating targeted learning outcomes so students can self-monitor their advancement and engage in metacognitive self-assessment. (3) Subject Matter, offering essential theoretical underpinnings to anchor cognitive engagement and strengthen conceptual comprehension. (4) Simulations, providing interactive, hands-on circuit experiments that prompt active engagement and promote deep cognitive processing. (5) Quizzes, supplying immediate, targeted feedback to reinforce metacognitive monitoring and encourage reflective refinement of learning strategies. Although the integration of this digital tool is designed to enhance both engagement and metacognitive growth, the present study does not aim to

validate the application's standalone efficacy experimentally. Rather, it focuses on examining how students' intrinsic capacities, specifically prior knowledge, metacognitive skills, cognitive engagement, and self-regulated learning, intersect to shape their critical thinking proficiency in resolving complex electrical circuit challenges. The interface of the learning application is presented in Fig. 2.

B. Participants

All participants were engineering students from the Faculty of Engineering, Universitas Negeri Padang, West Sumatra, Indonesia. They were selected from four academic programs in two disciplinary clusters, i.e., electronics and electrical education (engineering education) and electronics and electrical engineering (pure engineering). Purposive sampling was employed to include participants who had studied basic electrical theories, engaged in laboratory practicums, and consistently used learning technologies relevant to this study [34]. This technique ensured that participants met the academic and practical criteria of the study. However, it also has limitations, such as restricted generalizability, potential bias from non-random selection, and limited representation of students from other institutions or regions. Even so, the approach was considered appropriate because the selected students had mastered basic electrical theories and applied them using digital learning technologies in laboratory practice. Details of the respondents' characteristics are presented in Table 1.

Table 1. Respondent profile

Sample characteristics		Frequency	Percentage
Age	17–18 years old	9	2.4%
	19–20 years old	175	47.4%
	21–22 years old	139	37.7%
	23–24 years old	34	9.2%
	> 24 years old	12	3.3%
	Total	369	100%
Gender	Male	233	63.1%
	Female	136	36.9%
	Total	369	100%
Major	Electronics Engineering Education	104	28.2%
	Electrical Engineering Education	90	24.4%
	Electronics Engineering	94	25.5%
	Electrical Engineering	81	22%
	Total	369	100%
Duration of smart-phone use per day	1–3 h	13	3.5%
	4–6 h	118	32%
	7–9 h	119	32.2%
	More than 10 h	119	32.2%
	Total	369	100%

C. Measures

To measure the research variables, this study employed standardized research instruments adapted from previous studies. The instrument for assessing prior knowledge was adapted from [35]. The tool for measuring metacognitive was derived from [36]. Items for cognitive engagement were adopted from [37]. The instrument for self-regulated learning was sourced from [38]. The measurement tool for critical thinking disposition was taken from [39].

The adaptation process began with a literature review to identify established instruments for each variable, followed by the translation of all measurement items into the Indonesian language. An expert review was then conducted to ensure both linguistic appropriateness and cultural relevance, particularly by adjusting foreign terms to fit the current research context better. A pilot study was subsequently performed on a small sample outside the main study group to assess the clarity, validity, and reliability of the adapted instruments. Since these instruments were originally developed in different countries with diverse research contexts and cultural backgrounds, such validation and reliability testing were essential to confirm that the measurement items remained accurate and consistent within the present research setting.

After obtaining the primary data, further validity and reliability assessments were conducted using SEM analysis. At this stage, instrument validity was indicated by outer loading values greater than 0.70 and an Average Variance Extracted (AVE) exceeding 0.50.

$$AVE = \frac{\sum_{i=1}^{n} \lambda_i^2}{n} \tag{1}$$

Discriminant validity was confirmed using the fornell–larcker criterion and heterotrait-monotrait ratio (HTMT). The Fornell–Larcker criterion showed that the square root of AVE for each construct exceeded its correlations with other constructs, while all HTMT values were below 0.90, indicating that each construct was distinct and measured different concepts. Meanwhile, instrument reliability is confirmed through Cronbach's alpha and Composite Reliability (CR) values, both of which must exceed 0.70 [40, 41].

$$CR = \frac{(\sum_{i=1}^{n} \lambda_i)^2}{(\sum_{i=1}^{n} \lambda_i)^2 + (\sum_{i=1}^{n} \delta_i)} \tag{2}$$

The results of the validity and reliability analyses are presented in Table 2, Table 3, and Table 4.

Table 2. Instrument validity and reliability

Variable	Item	Outer loading	Cronbach's alpha	CR	AVE
Prior Knowledge	PK1	0.843	0.854	0.912	0.775
	PK2	0.887			
	PK3	0.909			
Metacognitive	Mc1	0.775	0.768	0.852	0.590
	Mc2	0.821			
	Mc3	0.749			
	Mc4	0.725			
Cognitive Engagement	CE1	0.895	0.853	0.911	0.773
	CE2	0.874			
	CE3	0.868			
Self-regulated Learning	SRL1	0.878	0.875	0.923	0.800
	SRL2	0.893			
	SRL3	0.913			
Critical Thinking Disposition	CTD1	0.921	0.889	0.931	0.819
	CTD2	0.864			
	CTD3	0.929			

Table 3. Fornell-Larcker criterion

Variable	CE	CTD	Mc	PK	SRL
CE	0.879				
CTD	0.871	0.905			
Mc	0.255	0.307	0.768		
PK	0.799	0.693	0.151	0.880	
SRL	0.859	0.891	0.321	0.720	0.895

Based on the analysis results, all constructs met the required criteria for validity and reliability. The outer loading values for all items exceeded 0.70. Each indicator made a significant contribution to its respective construct.

Additionally, all AVE values were above 0.50, while both the Cronbach's alpha and CR values demonstrated excellent reliability, with all constructs showing reliability scores above 0.70.

Table 4. HTMT

Variable	CE	CTD	Mc	PK	SRL
CE					
CTD	0.870				
Mc	0.262	0.283			
PK	0.739	0.650	0.118		
SRL	0.716	0.749	0.398	0.740	

Discriminant validity was assessed to evaluate the extent to which each construct in the model is conceptually distinct from the others. This was examined using the Fornell-Larcker criterion, which involves comparing the square root of the AVE for each construct with the correlations among the other constructs. As presented in Table 3, the square root AVE values on the diagonal for each construct are as follows: Cognitive Engagement (CE) = 0.879, Critical Thinking Disposition (CTD) = 0.905, Metacognition (MC) = 0.768, Prior Knowledge (PK) = 0.880, and Self-Regulated Learning (SRL) = 0.895. All diagonal values exceed the corresponding inter-construct correlation coefficients in their respective rows and columns. These results confirm that all constructs in the model exhibit satisfactory discriminant validity, measuring conceptually distinct dimensions. In addition, discriminant validity was further examined using the HTMT ratio of correlations. As shown in Table 4, all HTMT values fall below the threshold of 0.90, providing additional evidence that each construct is empirically distinct and that multicollinearity is not a concern in the measurement model.

Building upon this confirmation, additional data preprocessing steps were undertaken, including screening for missing values, checking for outliers, and ensuring the normal distribution of items. These steps were performed to improve data quality and prevent biased estimation. Beyond confirming the accuracy and reliability of the measurement instruments, this study also verified that the model is not prone to overfitting and demonstrates strong structural stability. This conclusion is reinforced by the positive Q^2_predict values obtained from PLSpredict [42], together with the Variance Inflation Factor (VIF) statistics < 5 [43].

Table 5. Overfitting

Item	RMSE	MAE	Q^2_predict
CE1	0.648	0.502	0.549
CE2	0.592	0.442	0.563
CE3	0.763	0.576	0.397
CTD1	0.760	0.583	0.402
CTD2	0.650	0.497	0.440
CTD3	0.724	0.547	0.411
SRL1	0.723	0.547	0.414
SRL2	0.728	0.529	0.415
SRL3	0.691	0.509	0.498

Table 5 presents the results of the PLS Predict test, indicating that all items yield positive Q^2_predict values, ranging from 0.397 to 0.563. This result suggests that the model demonstrates strong predictive relevance and is free from overfitting issues.

Table 6 reports the VIF values for each measurement item. Since all values fall below the recommended threshold of 5, the model can be considered structurally stable, free from multicollinearity issues, and indicative of well-controlled inter-variable bias.

Table 6. VIF

Item	VIF	Item	VIF
PK1	1.773	CE2	2.203
PK2	2.431	CE3	1.885
PK3	2.648	SRL1	1.983
Mc1	1.682	SRL2	2.701
Mc2	1.776	SRL3	2.975
Mc3	1.378	CTD1	3.002
Mc4	1.340	CTD2	2.141
CE1	2.434	CTD3	3.244

All measurement items fulfilled the necessary prerequisites for hypothesis testing, with validity and reliability adequately established, no signs of overfitting, and the model demonstrating stability. Consequently, the instruments utilized in this study can be regarded as both accurate and consistent in capturing the intended variables.

D. Data Analysis

All variables were measured using a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) [44]. Data collection was conducted through an online survey administered via Google Forms. The collected data were analyzed using two techniques. First, to test the research hypotheses, structural equation modeling (SEM) was conducted using SmartPLS 3. Additionally, to support the primary findings, a Fuzzy C-Means Clustering (FCM) analysis was performed using Jeffreys's Amazing Statistics Program (JASP). This supplementary analysis was conducted to categorize the data into groups based on respondent characteristics, providing an overview of the distribution of sample sizes across specific clusters.

IV. Result and Discussion

A. Hypothesis

In accordance with the conceptual framework of this study (see Fig. 1), eight direct relationships were formulated. The framework illustrates the influence of four independent variables, i.e., prior knowledge, metacognition, cognitive engagement, and self-regulated learning, on critical thinking disposition. In general, two criteria were applied to determine whether significant relationships exist among the variables. In general, two criteria were applied to determine whether significant relationships exist among the variables. First, statistical significance was assessed based on the *t*-statistic (greater than 1.96) and the *p*-value (less than 0.05) [45]. Second, the magnitude of the relationships was evaluated through the beta coefficient (path coefficient), which ranges from −1 to 1 [46]. The results of the hypothesis testing are presented in Fig. 3 (*T*-statistic) and Fig. 4 (*P*-value), as well as in Table 7.

Fig. 3 and Fig. 4 illustrate the structural model. Blue circles represent latent variables, and yellow rectangles denote observed indicators. Arrows indicate hypothesized causal paths, with associated path coefficients and significance values shown alongside. The model examines both direct and mediated effects of prior knowledge and metacognitive on critical thinking disposition, with cognitive engagement and self-regulated learning serving as mediators. To enhance reader understanding, Table 6 presents detailed values of the path coefficients (β), *t*-statistics, *p*-values, and the

corresponding hypothesis decisions.

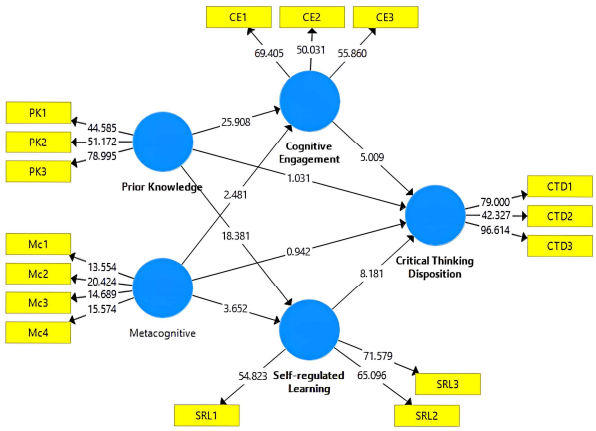

Fig. 3. T-statistic.

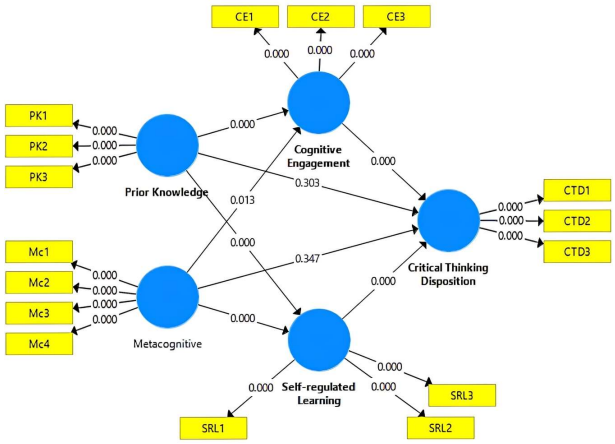

Fig. 4. P-value.

Table 7. Direct effect

	Direct Path	β	*T*-Statistic	*P*-Value	Result
H1	Prior Knowledge -> Cognitive Engagement	0.779	25.908	0.000	Supported
H2	Prior Knowledge -> Self-regulated Learning	0.668	18.381	0.000	Supported
H3	Prior Knowledge -> Critical Thinking Disposition	-0.053	1.031	0.303	Un-supported
H4	Cognitive Engagement -> Critical Thinking Disposition	0.441	5.009	0.000	Supported
H5	Metacognitive -> Self-regulated Learning	0.217	3.652	0.000	Supported
H6	Metacognitive -> Cognitive Engagement	0.137	2.481	0.013	Supported
H7	Metacognitive -> Critical Thinking Disposition	0.029	0.942	0.347	Un-supported
H8	Self-regulated Learning -> Critical Thinking Disposition	0.540	8.181	0.000	Supported

As shown in Table 7, out of the eight hypotheses tested, six yielded significant results and were thus supported, while the remaining two did not produce significant results and were therefore classified as unsupported. The analysis of H1 reveals that prior knowledge has a positive and significant effect on cognitive engagement, with a coefficient of β = 0.779, a *t*-statistic of 25.908, and a *p*-value of 0.000. Statistically, this finding suggests that the higher the students' prior knowledge, the greater their level of cognitive engagement in the learning process. The high coefficient indicates that the effect of prior knowledge on cognitive engagement is strong. Several previous studies have reported similar findings. For instance, Wang *et al.* [47] indicate a positive correlation between prior knowledge and cognitive engagement in game-based learning among university students. Similarly, Ng *et al.* [48] demonstrate that gamified learning, when implemented in secondary school students, can enhance cognitive engagement, particularly when supported by prior knowledge and clearly defined learning objectives. However, some findings suggest that prior knowledge may, in fact, increase cognitive load [49]. Therefore, the relationship between prior knowledge and cognitive engagement is not absolute but rather contingent upon the nature of the subjects and objects being examined. This connection exists because prior knowledge serves as a foundation for schema activation, which facilitates learning engagement. Nonetheless, under certain conditions, prior knowledge may intensify cognitive processing especially when new information is either misaligned or overly complex.

Consistent with H1, the results for H2 indicate that prior knowledge has a positive and significant impact on self-regulated learning, with β = 0.668, *t*-statistic = 18.381, and *p*-value = 0.000. This empirical result aligns with Zimmerman et al.'s theory of self-regulated learning [50], which highlights how personal factors, including prior knowledge, shape students' capacity for self-regulation. Xia *et al.* [51] also demonstrate that prior knowledge plays a significant role in shaping self-regulated learning among secondary school students in the context of English language learning. In contrast, several other hypotheses did not yield statistically significant results. Dong *et al.* [15] also suggest that the influence of prior knowledge on cognitive learning engagement may require specific mediating pathways, such as cognitive load and help-seeking behavior. However, not all of these mediating pathways were found to be statistically significant. This indicates that the relationship between prior knowledge and learning-related variables is not always direct or linear, but rather highly dependent on contextual factors such as material complexity, learner characteristics, and the instructional design employed.

In contrast to the first two hypotheses, H3 did not show a statistically significant effect of prior knowledge on critical thinking disposition, indicating that this hypothesis was not supported. The *p*-value of 1.031 exceeds the 0.05 threshold, and the *t*-statistic of 0.979 is below the critical value of 1.96. Moreover, the path coefficient (β = -0.053) indicates a weak negative relationship. This finding aligns with Widyaningsih and Sulisworo [52], who reported that prior knowledge does not significantly influence the development of students' critical thinking. In that study, critical thinking was found to be more strongly affected by other variables such as learning interest and instructional strategies, rather than by prior knowledge alone. However, this result stands in contrast to the findings of Kania *et al.* [53], who revealed that prior knowledge, particularly within the domain of mathematics, contributes positively to students' critical thinking capabilities. The researchers argued that a solid foundational understanding can enhance students' abilities to analyze,

evaluate, and synthesize information, which are the core components of critical thinking. These divergent findings suggest that the influence of prior knowledge on critical thinking disposition is highly contingent upon the learning context, the nature of the subject matter, and the pedagogical approaches employed.

The results for H4 indicate that cognitive engagement has a positive and significant effect on critical thinking disposition, as evidenced by $\beta = 0.441$, t-statistic = 5.009, and p-value = 0.000. This hypothesis is thus supported statistically. This finding supports several studies [54, 55], which show that the higher students' cognitive engagement in the learning process, the greater the likelihood they will demonstrate well-developed critical thinking. Nevertheless, cognitive engagement is not always the dominant factor in the development of a critical thinking disposition. Some studies argue that cognitive engagement serves only as one of many determinants. For instance, Hendekci [56] emphasizes that curiosity is the primary driver of critical thinking. Curiosity prompts students to ask questions and thoroughly evaluate information. Meanwhile, Makhrus and Hidayatullah [57], through the lens of cognitive dissonance theory, demonstrate that internal cognitive conflict can motivate individuals not to accept information at face value but instead to engage in critical evaluation before making decisions.

For H5, the results indicate a positive and significant effect of metacognition on self-regulated learning, with $\beta = 0.217$, t-statistic = 3.652, and p-value = 0.000. Therefore, H5 is supported statistically. Recent studies also corroborate this finding. Metacognitive ability has been shown to play an important role in the practice of self-regulated learning, particularly in online learning contexts [58]. Additionally, research conducted on prospective teachers revealed that the higher the level of metacognitive ability, the higher their level of self-regulated learning [59]. This aligns with the framework of self-regulated learning theory, which positions metacognition as one of the major factors. However, several studies have also indicated that metacognition does not directly influence self-regulated learning. A mediating factor, such as enthusiasm for learning, is required for metacognition to have an impact on self-regulated learning [60]. Therefore, although some research identifies metacognition as a major determinant, it sometimes requires other mediating variables to optimize the practice of self-regulated learning.

H6 provides evidence of a positive and significant effect of metacognition on cognitive engagement, as indicated by $\beta = 0.137$, t-statistic = 2.481, and p-value = 0.013. Therefore, H6 is empirically supported. Similar results were also found in previous studies showing that students with higher levels of metacognitive ability tend to be more actively engaged cognitively in the learning process [61]. Rationally, the relationship between metacognition and cognitive engagement can be explained by the function of metacognition as a regulatory mechanism of thinking processes. Through metacognitive awareness, students can monitor, evaluate, and adjust their cognitive strategies, which in turn stimulates deeper engagement with the learning material. However, metacognition alone is not sufficient to produce higher levels of cognitive engagement, particularly when students lack intrinsic motivation or a supportive learning environment [62]. Philosophically, this suggests that human cognition cannot be reduced merely to the ability to regulate thought processes. Engagement requires not only cognitive regulation (knowing how one thinks) but also an existential drive, such as motivation, curiosity, or even a sense of purpose, that orients the learner toward meaningful participation in learning. Thus, while metacognition is an important determinant, it is not the sole predictor of cognitive engagement. Rather, it functions as part of a broader constellation of factors, cognitive, motivational, and environmental, that together shape the depth of students' cognitive engagement in learning.

For H7, the relationship between metacognition and critical thinking disposition was not statistically significant. The path coefficient ($\beta = 0.029$) was very low, with a t-statistic of 0.942 and a p-value of 0.347, which is well above the significance threshold of 0.05. Thus, H7 was not supported statistically. Metacognition has long been associated with the development of critical thinking. For example, Raj *et al.* [63] and Teng and Yue [64] state that individuals who can monitor and evaluate their own thinking processes tend to have greater potential for reflective, analytical, and logical reasoning, core characteristics of critical thinking. However, the findings of this study align with those reported by Ossa *et al.* [65]. While the two are intrinsically interconnected, metacognitive functions operate as an overarching framework that orchestrates the thinking process, whereas critical thinking operates as the applied disposition within that framework. Metacognitive ability can indeed amplify the effectiveness of critical thinking, yet it is by no means the sole determining factor. Thus, the results indicate that there is no significant effect between metacognition and critical thinking. This, in fact, represents a factual strength showing that not all theoretical assumptions are empirically confirmed. This finding underscores that critical thinking does not rely solely on metacognitive but also requires the support of other factors such as motivation, critical thinking disposition, curiosity, and a stimulating learning environment.

In H8, the results indicate that self-regulated learning has a positive and significant effect on critical thinking disposition, with $\beta = 0.540$, t-statistic = 8.181, and p-value = 0.000. This finding demonstrates that the higher the students' self-regulation in learning, the stronger their critical thinking disposition. Self-regulated learning has been found to exert a positive influence on students' critical thinking abilities [66]. Furthermore, other studies emphasize that effective self-regulated learning, when combined with the use of interactive instructional modules, can significantly enhance critical thinking [67]. However, research has also reported that to achieve this relationship optimally, the presence of mediating factors is required, one of which is ease of use in technology integration [68]. This result implies that the impact of self-regulated learning on critical thinking cannot be separated from the extent to which the technologies employed in self-directed learning are easy to understand, accessible, and controllable for students. If learning technologies are overly complex or burdensome, students' efforts in self-regulation may be hindered, preventing them from achieving optimal outcomes in critical thinking.

Table 8 presents the results of the indirect effect analysis. In H9, cognitive engagement mediates the relationship

between prior knowledge and critical thinking disposition, with β = 0.061, t-statistic = 2.859, and p-value = 0.004. In addition, in H10 self-regulated learning also significantly mediates the effect of prior knowledge on critical thinking, with β = 0.344, t-statistic = 4.565, and p-value = 0.000. These findings suggest that prior knowledge does not directly influence the critical thinking disposition. Instead, its influence becomes significant when students are cognitively engaged and effectively self-regulate their learning processes.

The indirect effect analysis also shows that self-regulated learning and cognitive engagement mediate the relationship between metacognition and critical thinking disposition. In H11 and H12, the effect sizes are 0.117 and 0.372, respectively, with t-statistics of 2.832 and 8.260. The corresponding p-values, 0.005 and 0.000, further support the statistical significance of these mediating effects. This finding demonstrates that although metacognitive ability does not directly affect students' critical thinking, its impact becomes significant when channeled through well-planned learning strategies and deep cognitive engagement. In other words, the stronger the students' metacognition, the greater their critical thinking ability, provided they also maintain effective self-regulation and meaningful cognitive involvement.

Table 8. Indirect effect

	Indirect Path	β	*T*-Statistic	*P*-Value	Result
H9	Prior Knowledge -> Cognitive Engagement -> Critical Thinking Disposition	0.061	2.859	0.004	Supported
H10	Prior Knowledge -> Self-regulated Learning -> Critical Thinking Disposition	0.344	4.565	0.000	Supported
H11	Metacognitive -> Self-regulated Learning -> Critical Thinking Disposition	0.117	2.832	0.005	Supported
H12	Metacognitive -> Cognitive Engagement -> Critical Thinking Disposition	0.372	8.260	0.000	Supported

Theoretically, this phenomenon aligns with the principles of constructivist learning theory, which asserts that prior knowledge and metacognition are important prerequisites, yet insufficient on their own for cultivating robust critical thinking [69]. These skills serve as latent resources that only become fully actualized when students engage in cognitive processing and possess the capacity to manage their learning processes autonomously. This mechanism can be further illuminated through information processing theory, wherein cognitive engagement facilitates the transformation of knowledge from mere declarative forms into procedural and conditional knowledge, both of which are indispensable for critical thinking. Meanwhile, self-regulation empowers students to plan, monitor, and evaluate their thinking strategies, thereby enabling a more purposeful and effective utilization of prior knowledge and metacognitive abilities.

Building upon this theoretical foundation, previous empirical investigations have explored how technology-mediated learning, particularly through learning applications, can enhance students' competencies. The effectiveness of such applications is optimized when accompanied by appropriate supporting elements. A literature review study emphasized that the optimal utilization of learning apps requires a well-structured framework of learning regulation [70]. Furthermore, a meta-analysis conducted in the United States revealed that learning applications can significantly improve student achievement with an effect size of 0.31 [71]. In contrast to these earlier findings, the present study demonstrates that prior knowledge and metacognitive ability do not directly influence the disposition towards critical thinking. Their effects become significant when mediated through cognitive engagement and self-regulated learning. Field evidence suggests that the efficacy of learning applications does not solely rely on structured learning regulation or direct cognitive factors, but is significantly influenced by internal learner attributes, specifically cognitive involvement and self-regulation. The practical implications are clear: educators should design instructional practices that stimulate reflective activities, problem-solving, and systematically foster self-regulatory strategies. Meanwhile, developers of learning applications need to embed internationally recognized features such as interactive quizzes, gamification, adaptive feedback, progress monitoring, and study reminders. Therefore, learning applications serve not only as vehicles for content delivery but also as dual-purpose platforms that actively trigger cognitive engagement and nurture learner autonomy, ultimately strengthening the development of critical thinking disposition.

B. Clustering Analysis

The clustering procedure using fuzzy c-means (FCM) was performed with the assistance of JASP [72]. With a total sample of 369 respondents, the computation was completed in under five minutes. Execution time was not considered a limitation in the analysis. To ensure the robustness of the clustering results, the procedure was repeated with different random initializations. The outcomes consistently produced a relatively stable number of clusters across iterations. The detailed results of this analysis are presented in Table 9.

Table 9. Cluster information

Cluster	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Size	124	21	76	85	63
Explained proportion within-cluster heterogeneity	0.283	0.044	0.181	0.324	0.168
Cluster mean	0.210	−0.401	0.864	−0.829	−0.202
Category	Moderate	Passive	Active	Passive	Moderate

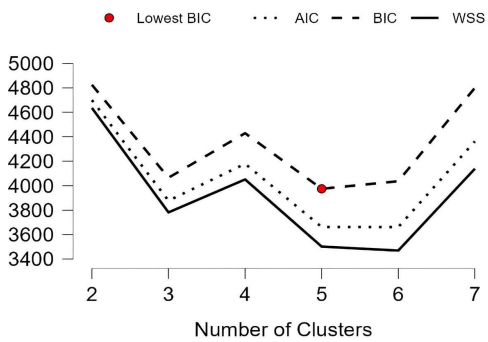

Fig. 5. Elbow plot.

Fig. 5 presents the model fit evaluation using internal validity indices (AIC, BIC, and WSS). The results indicate that the optimal clustering solution was obtained with 5

clusters, as reflected by the lowest BIC value. For interpretive clarity, these five clusters (in Fig. 6) were further categorized into three broader groups: passive, moderate, and active learners. It is important to note that these categories were not predefined ground-truth labels but rather emerged organically from the fuzzy c-means clustering algorithm. In the absence of external benchmark classes, supervised evaluation metrics such as F1-score or Purity are not applicable. Consequently, the quality of the clustering solution in this study was assessed using internal validity indices, which aligns with established practices in unsupervised clustering research [73].

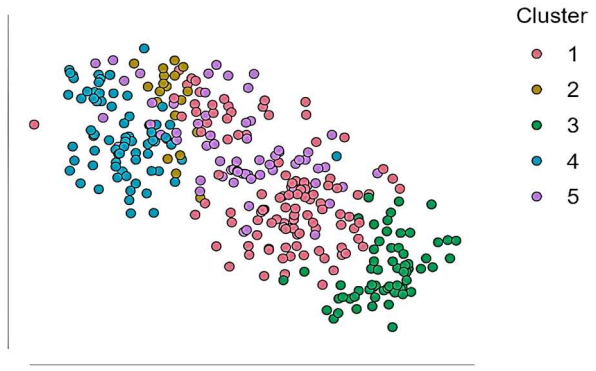

Fig. 6. t-SNE plot.

The mean value of each cluster was used to illustrate the level of user engagement in utilizing the learning application. This value represents the average behavioral characteristics of users within each cluster, consistent with the centroid-based segmentation theory. To ensure a more objective interpretation, a grand mean of −0.0716 was employed as the general reference point, reflecting the overall mean distribution of the population. Following the principles of standardized banding and established rule of thumb guidelines for score interpretation, the categorization thresholds were defined as follows clusters with a mean above 0.3 were classified as active, those with a mean between -0.3 and 0.3 were categorized as moderate, and clusters with a mean below −0.3 were labeled as passive. These thresholds were established to determine the relative position of each cluster in comparison to the population mean. Consequently, this classification approach does not rely solely on ranking but also considers the extent to which each group deviates from the overall mean.

The classification results indicate that Cluster 3, with a mean value of 0.864 and a sample size of 76 respondents, falls into the active category. This cluster suggests that respondents in this group exhibit high levels of engagement across the study variables, i.e., prior knowledge, metacognition, cognitive engagement, self-regulated learning, and critical thinking.

In cluster 1, the mean value is 0.210, while Cluster 5 has a mean of −0.202, both fall into the moderate category. The sample sizes for these clusters are 124 and 63, respectively, meaning that a total of 187 respondents demonstrate engagement levels around the overall average. Users in this group utilize the learning application with reasonable consistency but not yet to an optimal level. They may still face challenges such as limited motivation or inadequate learning strategies, although they have the potential to increase their level of engagement.

In cluster 2, the mean value is -0.401, while Cluster 4 has a mean of −0.829, both are categorized as passive groups. The sample sizes for these clusters are 21 and 85, respectively, indicating that a total of 106 respondents show lower mean scores across most of the measured disposition. This suggests that participants in these groups tend not to actively utilize the learning application. Such tendencies may be attributed to limited learning readiness, low prior knowledge, or negative attitudes toward using technology in the learning process.

The conclusion drawn from this classification indicates that most users demonstrate moderate to low levels of engagement. The need for targeted strategies to increase engagement among moderate users and reduce the proportion of passive users to optimize the effectiveness of the learning application. This finding reinforces the importance of interventions tailored to the characteristics of each cluster. Active users can continue to be supported with advanced learning features, while moderate and passive groups require more fundamental approaches, such as training in learning strategies or enhancing digital literacy.

C. *Comparison with Previous Studies*

In order to frame the outcomes of this study within an international perspective, Table 10 outlines a cross-study comparison between the present evidence and earlier scholarly findings. This comparison highlights both areas of convergence and points of divergence.

Table 10. Comparison with previous studies

Author(s) / Year	Context & Participants	Method & Variables	Key Findings	Comparison with Current Study
Winarti *et al.* (2022) [74]	Physics education & senior high school students	Quasi-experimental study & metacognitive, self-regulated learning	The findings reveal that metacognitive is positively associated with students' self-regulated learning in the context of physics education.	These results support the present study, suggesting that both senior high school students and university students exhibit a positive linkage between metacognition and self-regulated learning.
Kania *et al.* (2023) [53]	Mathematics education & senior high school students	Correlational study & prior knowledge, critical thinking skills	There exists a positive linkage between prior knowledge and high school students' critical thinking within the realm of mathematics learning.	The findings diverge from the present study, which reveals that prior knowledge exerts no significant influence on engineering students' critical thinking when utilizing a learning app.
Ossa *et al.* (2023) [65]	Teacher education & university students	Correlational study & critical thinking, motivation, and metacognition	There is no significant direct relationship between metacognition and students' critical thinking. However, the connection becomes significant when mediated by the factor of motivation.	Prior research exhibits a pattern closely aligned with the present study. In that work, the mediating effect between metacognition and critical thinking was shaped by motivation, whereas in the current investigation the effect is mediated through self-regulated learning and cognitive engagement.

Kuhlmann *et al*. (2024) [75]	Instructional videos & biology undergraduate students	Quantitative experimental study & prior knowledge, cognitive engagement	Active engagement with video enhances learning outcomes, but only for students with low prior knowledge. Prior knowledge serves as a moderator in the relationship between cognitive engagement and learning achievement.	The results support the current investigation, indicating that cognitive engagement mediates the effect of prior knowledge on students' critical thinking when utilizing a learning application.

V. Conclusion

Students have successfully adopted the implementation of learning application as part of an effort to create a more innovative and high-quality educational environment. This initiative aligns with the goals of the Sustainable Development Goals (SDGs), particularly the objective of improving the quality of education. Several empirical insights have been gleaned from the field data. Among the variables analyzed, i.e., prior knowledge, metacognition, cognitive engagement, and self-regulated learning, each contributes in its own way, with some exerting a direct influence and others an indirect one. Consequently, these factors cannot operate in isolation. Instead, they require reinforcement from one another. For instance, prior knowledge, without robust cognitive engagement and effective self-regulated learning, is insufficient to optimally enhance critical thinking. The same holds for metacognition. The results highlight that without strong cognitive engagement and well-developed self-regulated learning, the effects of prior knowledge and metacognitive skills on students' critical thinking remain limited. Furthermore, based on the clustering results, the majority of students fell into the moderate category for prior knowledge, metacognitive, cognitive engagement, and critical thinking disposition, followed by the passive and active categories. Students' competencies across these dimensions still require substantial enhancement.

From a theoretical perspective, these findings deepen our understanding of psychological and cognitive factors, particularly prior knowledge, metacognition, cognitive engagement, and self-regulated learning, in shaping students' critical thinking in a digital learning environment. From a methodological standpoint, integrating structural equation modeling (SmartPLS 3) with Fuzzy C-Means Clustering (JASP) provides a complementary analytical approach that not only uncovers complex causal relationships but also highlights meaningful group patterns among respondents.

Several practical implications emerge from both the SEM analysis and the clustering results. Based on the hypothesis testing using SEM, educators should design learning experiences that foster cognitive engagement, such as problem-based projects, inquiry tasks, and reflective discussions, while guiding students in self-regulated learning. These can be strengthened with targeted interventions, including adaptive feedback for personalized guidance, reflective gamification for deeper self-assessment, and activity-based notifications to prompt timely engagement, thereby maximizing the impact of prior knowledge and metacognitive on critical thinking development. Application developers should also consider designing applications that are both engaging and easy to use to attract and retain users' interest. Additionally, the clustering results suggest providing adaptive feedback to guide moderate-group students toward higher proficiency, utilizing reflective gamification and activity-based notifications to enhance skills in the passive group, and designing collaborative challenges for the active group to sustain and expand their abilities. Despite these contributions, this study has certain limitations. Potential latent bias may arise from the use of self-reported data, and there may be a mismatch between the theoretical constructs (e.g., prior knowledge, metacognitive) and their practical application in the observed learning context.

Furthermore, the absence of direct effects for some variables may indicate the need to examine potential mediating or moderating factors in future research. In addition, the sample in this study was limited to students majoring in electronic engineering and electrical engineering, both in pure and educational programs. Therefore, future research is recommended to refine the research instruments, for instance, by employing well-structured test items. Moreover, it is also advisable to broaden the scope of investigation to other engineering disciplines, such as civil, chemical, and industrial engineering, as well as beyond.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Hendra Hidayat: drafting manuscript, methodology section, and research design. Hafizul Fahri Hanafi: collecting data and statistical analysis. Muhammad Anwar: research design. Hadi Kurnia Saputra: collecting data and methodology section. Anggarda Paramita Muji: statistical analysis. Randi Proska Sandra: revising the manuscript. All authors have accepted the final version of the manuscript.

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