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Original Research Article

Mental Model-Based Learning: Advancing Critical Thinking of Pre-Service Elementary School Teachers in the Digital Era

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Abstract: Learning innovation for pre-service Madrasah Ibtidaiyah (MI) teachers is essential to address the challenges of the digital era. The digital technology era requires critical thinking skills to integrate information and knowledge comprehensively. This study aims to examine the effectiveness of mental model-based learning in enhancing the critical thinking abilities of pre-service Islamic Primary School Teacher Education students in the era of disruption. The research employed a quantitative approach with a quasi-experimental non-equivalent control group design. The research subjects consisted of two groups: an experimental group (30 pre-service teachers) and a control group (30 pre-service teachers). The research instrument comprised a critical thinking test based on Facione's indicators. Data analysis used t-test, N-Gain, and effect size. The results demonstrate that mental model-based learning significantly improved students' critical thinking abilities, with an N-Gain of 0.51 (medium-high category) and an effect size of 0.85 (large category). These findings indicate that the mental model approach is effective in developing critical thinking skills through cognitive simulation and technology integration in learning for pre-service MI teachers. This study contributes to the development of innovative learning models to improve the quality of teacher education in the era of disruption.

Keywords: Critical Thinking, Digital Era, Innovation, Mental Model.

A. INTRODUCTION

The era of disruption, characterized by advances in artificial intelligence (AI), the COVID-19 pandemic, and the Fourth Industrial Revolution (Industry 4.0), has radically transformed educational paradigms. This transformation demands that educators rapidly adapt to disruptive technologies such as machine learning and the metaverse, shifting the role of teachers from mere information transmitters to critical facilitators (UNESCO, 2023). Technological advancements enable personalized learning, yet also generate risks of misinformation that require critical detection (Selwyn, 2022). The COVID-19 pandemic accelerated the transition toward hybrid learning, revealing an excessive dependence on digital literacy (UNESCO, 2021). Industry 4.0 emphasizes human-machine collaboration skills. Pre-service elementary school teachers must possess the ability to train students to predict future scenarios through cognitive simulation. The low adoption of technology has caused many elementary school teachers to lack an adequate understanding of AI applications. Consequently, critical learning innovation has become an imperative for building educational resilience in the post-disruption era.

At the global level, the World Economic Forum (2023) predicts that many jobs will be displaced by automation while new types of employment will emerge. Primary education is key to the resilience of the future workforce. This prediction underscores the necessity of non-routine skills such as critical thinking to thrive in an AI-driven digital era. The PISA 2022 survey revealed a critical thinking deficit in developing countries, with the OECD average score reaching 487 points as a benchmark (OECD, 2023). These low scores reflect a quality gap in

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primary education. Furthermore, TIMSS 2023 data indicate that the critical mathematics performance of primary school students has stagnated in the post-pandemic period (Mullis *et al*., 2024). This deficit risks undermining the competitiveness of the younger generation, particularly in an education sector that requires innovative teachers. Therefore, reforming critical thinking from the primary level has become an urgent priority to mitigate disruption in the digital era.

Indonesia faces similar challenges, as PISA 2022 recorded critical thinking scores among 15-year-old students far below the OECD average. TIMSS 2019 indicated that the mathematical analytical abilities of students at the primary education level remain low (Mullis *et al.,* 2020). These data reflect the unpreparedness of the educational system to face digital disruption, as not all primary educational institutions have adequate internet access. The impact is evident in post-pandemic learning loss, in which 60% of elementary school students lost basic analytical competencies. This unpreparedness is influenced by the failure of learning transitions to emphasize critical simulation (Nugroho, 2025). Urgent reform is needed to align primary education with the demands of Industry 5.0.

Primary education, as the foundation of the national educational system, is most vulnerable because its curriculum remains dominated by rote memorization with limited technology integration (Sahniarti & Sirozi, 2025). The COVID-19 pandemic caused the majority of students and pre-service primary school teachers to experience learning loss, particularly in the domains of higher-order thinking, analysis, and problem-solving. Learning in the digital era demands adaptive abilities from an early age (Selwyn, 2022). The majority of pre-service Madrasah Ibtidaiyah teachers (pre-service MI teachers) at Universitas Islam Negeri Maulana Malik Ibrahim Malang encounter difficulties in integrating technology into teaching simulations. Therefore, reform in primary education learning must be prioritized to build a foundation for disruption resilience.

Pre-service Madrasah Ibtidaiyah teachers, as the vanguard of Islamic primary education, are often insufficiently prepared to integrate disruptive technologies, which in turn renders Madrasah Ibtidaiyah students non-adaptive to digitalization. Surveys indicate that many pre-service teacher graduates lack digital literacy competencies for interactive teaching. According to Hidayat (2025), pre-service MI teacher students frequently struggle to map problems particularly digital ethics simulations in the learning context. This condition may impair their ability to verify online content, increasing the risk of digital radicalization. Learning remains predominantly theory-based with minimal adaptive critical thinking practice (Kahar & Hasri, 2023). Reform in pre-service teacher education is needed to synchronize conceptual understanding with technological disruption so as to prepare teachers for the digital era.

Conventional learning often fails to develop 21st-century competencies such as critical thinking, which is essential for navigating disruption in the digital era. Facione (2021) defines critical thinking as a process involving interpretation, analysis, evaluation, inference, explanation, and self-regulation. However, the learning practices of pre-service MI teachers still predominantly employ a lecture-centered approach. This method does not stimulate cognitive simulation for disruption issues in digital-era learning in MI contexts. Ennis (2018) emphasizes critical thinking as a rational disposition, yet observations reveal that interactive activities remain scarce. The lack of activities and interaction neglects the measurement of argumentation quality. In the age of the metaverse, pre-service MI teachers need to be facilitated in virtual debates, not merely engaged in fact transfer. A transition toward active models such as mental model-based learning represents an effective alternative for enhancing 21st-century skills in the digital era.

Learning innovation is necessary to bridge the critical gap among pre-service MI teachers, with a focus on cognitive models that support complex simulations in the digital era. Mental models constitute internal mental representations for understanding and predicting phenomena (Johnson-Laird, 1983), offering a promising framework through the visualization of causal relationships and structural analogies (Swinburne Romine *et al*., 2025). This theory enables pre-service MI students to simulate scenarios digitally within the learning environment. Shen *et al*., (2017) demonstrated that mental models enhance knowledge transfer in learning. Compared to conventional instruction, mental models are superior for the visualization of abstract concepts such as educational metaverses (Swinburne Romine *et al*., 2025). Consequently, this innovation is ideal for adaptive learning in the digital era.

Mental model theory has been proven effective in improving learning quality. Gentner and Smith (2022) reported improvements in students' problem-solving understanding through structural analogies. Hockly (2000) found significant gains in critical thinking among pre-service teachers through cognitive simulation. A meta-analytic study by Aipah *et al*., (2024) confirmed a large effect size for mental models in global teacher training contexts. Similarly, Kim and Cho (2025) found that mental model adaptations can improve the analytical abilities of pre-service teachers. Such adaptations can integrate students' existing knowledge with simulations of disruption in the digital era. However, no specific digital module for teachers designed for use in this learning context has yet been developed (Kahar & Hasri, 2023).

Based on both empirical and theoretical evidence, learning innovation grounded in mental

models is needed to prepare pre-service MI teachers for the digital era, with mental models serving as a cognitive bridge toward adaptive critical thinking. This approach not only enhances critical thinking abilities but also integrates knowledge within digital simulations. This study aims to examine the contribution of mental model-based learning to the development of critical thinking among pre-service primary school teachers. The research may contribute to establishing a foundation of resilience for Islamic primary education amid the waves of global disruption.

B. METHODS

This study employed a quantitative approach with a quasi-experimental non-equivalent control group design, aimed at examining the effectiveness of mental model-based learning in improving the critical thinking abilities of pre-service Islamic Primary School Teacher Education students. This design was selected because it allows researchers to compare the experimental and control groups without full randomization, while still providing adequate internal validity in educational contexts (Creswell & Creswell, 2018). The experimental group received the treatment (mental model-based learning), while the control group continued with conventional instruction. This approach enables analysis of changes in critical thinking abilities before and after the intervention, as well as comparisons between groups (Fraenkel *et al*., 2019).

The research subjects were students of the pre-service teacher Study Program at Universitas Islam Negeri Maulana Malik Ibrahim Malang in the 2025-2026 academic year. Subject selection employed a purposive sampling technique, considering that the students had completed foundational pedagogical courses and possessed preliminary experience in teaching practice. The sample comprised 30 students in the experimental group and 30 students in the control group. The characteristics of the subjects were relatively homogeneous in terms of age, educational background, and prior experience with educational technology.

This study involved mental model-based learning as the treatment and critical thinking ability as the measured variable. Critical thinking ability was assessed based on indicators developed from Facione (2021) and Ennis (2018), encompassing: interpretation, analysis, evaluation, inference, explanation, and self-regulation. Questionnaires were employed to examine the engagement and responses of the pre-service teachers.

The study was conducted in several phases. The Preparation Phase involved developing mental model-based learning materials integrated with digital technology, validating the instruments by experts in education and educational technology, and measuring instrument validity and reliability. The calculation results showed that the instrument was valid, with a Cronbach's Alpha value of 0.89 and a validity value of 0.81. Normality and homogeneity tests indicated that the samples were normally distributed and homogeneous. The validity and reliability results are presented in Table 1, while the normality and homogeneity of the sample are presented in Table 2.

Table 1: The results of the reliability

Cronbach's Alpha	Validity
0,89	0,81

Tabel 2: Normality and Homogeneity of the Sample

Test	Statistic	df	p-value	Interpretation
Kolmogorov–Smirnov (Exp pre)	0.120	–	.735	Normal (p>.05)
Kolmogorov–Smirnov (Exp post)	0.149	–	.472	Normal (p>.05)
Kolmogorov–Smirnov (Ctrl pre)	0.136	–	.592	Normal (p>.05)
Kolmogorov–Smirnov (Ctrl post)	0.089	–	.953	Normal (p>.05)
Levene’s test (Pre-scores)	0.64	1,58	.427	Homogeneous var.
Levene’s test (Post-scores)	0.24	1,58	.623	Homogeneous var.

The Implementation Phase involved administering a pre-test to both groups, followed by 6–8 instructional sessions. The experimental group employed the mental model approach through cognitive simulation, visualization of causal relationships, and analogy mapping (Johnson-Laird, 1983; Gentner & Smith, 2022), while the control group used conventional methods (lecturing-centered). Upon completion of the learning sessions, a post-test was administered to both groups. The Evaluation Phase comprised analysis of improvements in critical thinking ability and comparison of results between the experimental and control groups.

C. RESULT & DISCUSSION

The pre-test results indicated that the critical thinking abilities of pre-service MI teachers in both groups were relatively equivalent. The mean initial score of the experimental group was 56.32, while that of the control group was 55.87, indicating no significant difference in the initial conditions. After the treatment, improvements were observed in both groups; however, the improvement in the experimental group was markedly more significant. The mean post-test score of the experimental group reached 78.45, while that of the control group was only 66.12. The detailed results are presented in Table 3.

Table 3: Pre-test and Post-test Mean Scores

Group	Pretest Mean (SD)	Posttest Mean (SD)
Experimental	56.32 (10.0)	78.45 (13.9)
Control	55.87 (10.0)	66.12 (14.9)

Table 3 shows that treatment with mental model-based learning can improve the critical thinking ability of pre-service MI teachers. This is supported by the t-test results, which indicate a significant difference between the experimental and control groups. The detailed t-test results are presented in Table 4

Table 4: T-test Results of Mental Model-Based Learning

Comparison	t (df)	p-value	Mean Δ
Experimental (Pre vs Post)	9.39 (29)	<.001	+22.13
Control (Pre vs Post)	4.37 (29)	<.001	+10.25
Exp vs Ctrl (Posttest)	3.31 (58)	.0016	+12.33

The t-test results indicate that the calculated t-value (3.31) exceeds the t-table value (1.672). This demonstrates that digital mental model-based learning can influence the critical thinking ability of pre-service MI teachers. The N-Gain results also show that the experimental group (0.51) outperformed the control group (0.23). The effect size was in the strong category (0.85). The N-Gain and effect size are presented in detail in Table 5.

Table 5: N-Gain and Effect Size of Mental Model-Based Learning

Contrast/Group	Cohen's d (pooled)	Interpretation	Mean N-gain	Gain category
Experimental (pre→post)	1.72 (very large)	Very strong	0.51	Medium–High
Control (pre→post)	0.80 (large)	Strong	0.23	Low
Posttest (Exp vs Ctrl)	0.85 (large)	Strong	–	–

The results demonstrate that mental model-based learning significantly improves the critical thinking ability of pre-service teachers compared to conventional approaches. These findings reinforce the mental model theory proposed by Philip Johnson-Laird (1983), which posits that internal mental representations enable individuals to understand, predict, and evaluate complex phenomena more systematically. In the learning context, the construction of mental models assists students in establishing causal relationships between concepts, thereby promoting higher-order thinking processes such as analysis, inference, and evaluation.

These findings are consistent with the research of Batlolona and Diantoro (2023), who demonstrated that the development of mental models contributes significantly to improvements in higher-order thinking abilities in science learning. Additionally, a systematic review by Rasyid *et al*., (2024) confirmed that constructivist approaches including the use of cognitive representations such as mental models are effective in improving critical thinking skills through problem-based learning and reflection. This perspective is further reinforced by Peter Facione (2021) and Robert Ennis (2018), who emphasize that critical thinking encompasses a combination of cognitive abilities and reflective dispositions that develop optimally through active learning.

Nevertheless, although numerous studies have confirmed the effectiveness of mental models in educational contexts and pre-service teacher education, significant research gaps remain. Most studies have focused on general or science education contexts, with limited research on Islamic-based teacher education such as pre-service MI teacher education. Prior research has tended to position mental models as cognitive tools without integration with religious values and digital ethics critical aspects of Madrasah education. Furthermore, studies linking mental models with disruption issues in the digital era, such as artificial intelligence (AI), digital literacy, and virtual simulation-based learning in pre-service MI teacher education, remain scarce. The majority of studies have yet to develop learning models integrated with interactive digital platforms, and their implementation within the 21st-century learning context remains limited.

The comprehensive integration of the mental model approach, critical thinking development, and the digital disruption context in pre-service MI teacher education is imperative. Developing contextual, integrative, and adaptive learning to meet the needs of digital-era education is essential for enhancing the 21st-century skills of pre-service MI teachers. The significant improvements observed in the experimental group demonstrate that the use of mental models can motivate students to engage in higher-order thinking processes such as analysis, inference, and evaluation. This aligns with the perspective of Peter Facione (2021), who emphasizes that critical thinking encompasses a series of complex cognitive processes ranging from interpretation to self-regulation. Accordingly, learning that facilitates the construction of mental models has the potential to strengthen all of these dimensions simultaneously.

The mental model approach enables students to organize knowledge in the form of structured internal representations. According to Philip Johnson-Laird (1983), mental models assist individuals in understanding complex systems through cognitive simulation. In the educational context, this is particularly important because students do not merely memorize concepts but develop a deep understanding of the interrelationships between variables. In the present study, students were not passive recipients of information but actively constructed causal relationships between concepts. This activity reflects a high level of cognitive engagement that rarely emerges in conventional learning. The process strengthens deep reasoning ability the capacity to grasp the meaning beneath information and connect it to broader contexts. According to Ennis (2018), critical thinking is not solely about analytical ability but also the ability to evaluate arguments reflectively and rationally. Therefore, mental model-based learning creates space for the development of both aspects.

These findings are further supported by the research of Gentner and Smith (2022), who showed that the use of analogies in mental models can enhance knowledge transfer and conceptual understanding. Analogies help students connect new concepts with existing knowledge, thereby strengthening their cognitive structure. In addition, a study by Adams *et al*., (2022) demonstrated that cognitive simulation-based learning can significantly improve the critical thinking ability of pre-service teachers. This occurs because students are trained to solve complex problems through exploration and reflection, rather than simply receiving answers.

Mental model-based learning is consistent with the principle that knowledge is actively constructed by the individual. According to Piaget (1970), the processes of assimilation and accommodation enable individuals to adjust their cognitive structures in response to new experiences. In this context, mental models serve as tools for meaningfully integrating those experiences. Mental model learning holds particular relevance because it enables the integration of knowledge with Islamic values. Students not only understand technology as a concept but also become capable of evaluating its ethical implications in teaching practice. This is especially significant in confronting the challenges of the digital disruption era. Mental model-based learning also fosters greater student engagement in the learning process. Research by Aipah *et al*., (2024) found that cognitive model-based approaches yield a sufficiently high effect size in improving higher-order thinking skills, indicating that this approach is not only theoretically effective but also empirically validated.

The use of mental models in learning makes a significant contribution to the development of students' critical thinking. This approach not only enhances analytical and evaluative abilities but also promotes a deeper and more contextual integration of knowledge. These results indicate that the implementation of mental models constitutes a relevant strategy for improving the quality of teacher education in the era of disruption.

The effectiveness of mental model-based learning is inseparable from the important role of visualization and structural analogy in supporting the knowledge construction process. Visualization enables students to represent abstract concepts in more concrete forms, facilitating an understanding of the relationships between concepts. Analogy, in turn, functions as a cognitive bridge connecting prior knowledge with more complex new concepts. According to Gentner and Smith (2022), analogy plays a crucial role in the knowledge transfer process because it allows individuals to recognize structural similarities between two different domains. This process not only aids comprehension but can also enhance critical thinking ability through the identification of patterns and conceptual relationships. Research findings indicate that pre-service teachers' ability to connect concepts with modern technological phenomena such as algorithms and artificial intelligence is highly commendable. This integration demonstrates that students as pre-service MI teachers do not merely understand concepts in isolation but can construct cross-domain understanding that is contextual and reflective.

The ability of pre-service MI teachers to connect concepts with the aid of digital technology reflects the occurrence of a deep process of analogical reasoning. Pre-service teachers were able to identify similarities between natural phenomena explained from a religious perspective and the operational principles of modern technology. This reinforces the argument that mental model-based learning can develop cognitive flexibility in understanding various complex phenomena.

The use of visualization in learning also contributes to improvements in the quality of conceptual understanding. Visual representations help students see cause-and-effect relationships more clearly, thereby supporting the processes of analysis and evaluation. In this regard, visualization becomes an essential tool in constructing accurate and structured mental models. These findings are consistent with research by Adams *et al*., (2022), which demonstrated that cognitive simulation-based learning can improve problem-solving abilities and critical thinking among pre-service teachers. Simulation enables students to explore various possible solutions through a model-based approach, thereby strengthening rational decision-making processes. Adams *et al*., (2022) also confirmed that students' active engagement in the simulation process is a primary factor in improving cognitive abilities. When students are directly involved in building and testing mental models, they tend to develop a deeper understanding of concepts compared with passive learning methods.

From a pedagogical perspective, the integration of visualization and analogy in mental model-based learning reflects a constructivist approach that emphasizes the active role of learners in constructing knowledge. This approach provides space for students to explore, reflect upon, and develop understanding independently. The effectiveness of mental models in improving critical thinking does not depend solely on the cognitive structures constructed, but also on the instructional strategies employed particularly through visualization and analogy. The combination of these two elements has been proven capable of strengthening knowledge transfer, improving conceptual understanding, and promoting students' analytical abilities in navigating the complexity of learning in the era of disruption.

The research findings reveal significant implications for the development of learning for pre-service MI teachers, particularly in responding to the challenges of digital disruption. Learning can no longer focus solely on content mastery but must be directed toward strengthening critical, adaptive, and contextual thinking abilities. Mental model-based learning offers an approach capable of bridging the gap between conceptual mastery and readiness to face rapid technological change.

A central implication is the importance of integrating conceptual knowledge and digital technology in the learning process. The mental model approach enables students to construct an understanding that connects religious concepts with contemporary digital-based phenomena. This integration is essential to ensure that pre-service teachers not only understand digital technology technically but are also capable of contextualizing it within a framework of values and ethics (Al-Attas, 1991). Accordingly, learning for pre-service MI teachers must be designed holistically to harmonize spiritual and digital dimensions in a balanced manner.

Mental model-based learning has the potential to develop artificial intelligence (AI) literacy grounded in ethics. Students are encouraged not only to use technology but also to evaluate its social, moral, and pedagogical impacts. This is increasingly important amid the rapid advancement of AI, which demands critical awareness and ethical responsibility in educational practice (Selwyn, 2022). Learning for pre-service MI teachers must incorporate aspects of critical digital literacy as part of the core competencies of prospective teachers.

The readiness of pre-service teachers to engage with future learning models such as hybrid learning, and metaverse-based learning environments is equally essential. The mental model approach helps pre-service MI teacher students build flexible and adaptive knowledge structures capable of accommodating various educational technology innovations. This need aligns with the demands of the Fourth Industrial Revolution (Industry 4.0) and Society 5.0, which emphasize the integration of cognitive abilities, technology, and human values (Schwab, 2016; Fukuyama, 2018). Consequently, pre-service teachers are expected to become innovative and responsive learning facilitators capable of adapting to contemporary developments.

The research findings also show a high effect size (0.85), indicating that mental model-based learning not only yields statistically significant results but also has a practically strong impact in the teacher education context. The intervention demonstrates high effectiveness in improving critical thinking ability. Therefore, this approach merits consideration as one of the alternative instructional strategies for pre-service MI teachers to produce graduates who are competent, adaptive, and competitive in the era of disruption.

This study makes significant theoretical contributions by reinforcing the concept of mental models in the context of Islamic education. Additionally, it contributes to the integration of cognitive learning and digital disruption issues. In the digital era marked by the development of artificial intelligence and technology-based learning transformation an approach is needed that not only develops technical competencies but also critical and ethical thinking abilities. This is consistent with the view of Klaus Schwab (2016), who emphasizes that the Fourth Industrial Revolution demands the integration of cognitive, technological, and humanistic competencies. Consequently, mental model-based learning becomes relevant as a bridge between cognitive aspects, the challenges of modern technology, and providing a new perspective on the construction of mental representations that are relevant to a deeper and more reflective understanding of concepts.

The integration of mental models, learning concepts, and technology simulations such as artificial intelligence and the metaverse constitutes an alternative learning solution for enhancing comprehensive and critical understanding. The combination of these three aspects within a single learning framework offers a more contextual and relevant model for educational needs in the era of disruption. The contributions and findings of this study provide a strong foundation for the development of learning practices for pre-service MI teachers. The learning model is not only oriented toward improving critical thinking ability but also toward character formation and ethics-based digital literacy.

D. CONCLUSION

This study demonstrates that mental model-based learning significantly improves the critical thinking ability of pre-service teachers compared to conventional instruction. This is evidenced by a higher post-test score increase in the experimental group, an N-Gain in the medium-high category, and a large effect size

(0.85) indicating a strong practical impact. The mental model approach has been proven effective in encouraging students to conduct cognitive simulation, construct causal relationships, and integrate abstract concepts within real-world contexts particularly regarding disruption issues in the digital era. Mental model-based learning represents a relevant and effective strategy for improving the quality of Madrasah Ibtidaiyah teacher education in the digital era.

Further research involving a broader and cross-regional sample is needed to enhance the generalizability of the findings. In addition, the development of more interactive mental model-based digital modules for example by leveraging virtual reality (VR) or metaverse technology is required to render learning more contextual and immersive. Future research is also needed to examine the relationship between mental models, self-regulated learning, and student engagement, to obtain a more comprehensive understanding of the factors influencing the effectiveness of learning in improving critical thinking skill.

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