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Uncovering Critical Thinking and Mathematical Representation Skills of Pre-Service Elementary Teachers Through Cognitive Style

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ABSTRACT: This study examines the critical thinking and mathematical representation abilities of pre-service elementary school teachers' students (PESTS) through the lens of field-dependent (FD) and field-independent (FI) cognitive styles. Using a qualitative descriptive approach, 39 participants completed the Group Embedded Figures Test (GEFT), problem-solving tasks, and semi-structured interviews to assess cognitive styles and representation skills. Results indicate that FD participants struggled with problem-solving, relying on prior experiences, providing superficial solutions, and using primarily symbolic and numerical representations with limited abstraction. In contrast, FI participants demonstrated more assertive critical thinking, systematically employing diverse representations including symbols, mathematical expressions, and verbal explanations to solve problems independently. These differences underscore the need for differentiated instruction, with the FD learners requiring structured support to enhance critical thinking and broaden their representation skills. The FI learners should be challenged with abstract and complex tasks to enhance their skills further. Personalized, adaptive learning strategies are essential to preparing future educators for the challenges of 21st-century teaching.

Keywords: primary teacher, mathematics, critical thinking, mathematical representation, cognitive style.

I. INTRODUCTION

Critical thinking is a pivotal skill in 21st-century education, encompassing analysis, interpretation, evaluation, inference, and self-regulation [1, 2]. In mathematics education, critical thinking facilitates logical reasoning, problem-solving, and abstract thinking, which are essential for both learners and educators [3]. The integration of critical thinking into mathematics pedagogy enhances students' analytical abilities and strengthens their problem-solving skills, making it a key focus in teacher education programs [4, 5]. For pre-service elementary school teachers' students (PESTS), mastery of critical thinking is indispensable, as it directly influences teaching effectiveness and students' intellectual development [6]. Mathematics educators require a strong foundation in critical thinking to facilitate learning and cultivate students' reasoning abilities [7]. However, deficiencies in these skills can hinder their capacity to foster deep mathematical understanding, affecting both their instructional quality and student outcomes [8]. Therefore, aspiring educators must not only develop their critical thinking but also acquire effective strategies to enhance students' reasoning skills [9].

In addition to critical thinking, mathematical representation is a fundamental competency for effective mathematics instruction. It enables teachers to translate abstract concepts into visual, symbolic, and verbal forms, enhancing comprehension and problem-solving abilities [10]. For PESTS, proficiency in mathematical representation is essential to effectively convey mathematical ideas and support students in developing their representational skills a key factor in conceptual understanding [11, 12]. Research highlights the strong correlation between teachers' representational proficiency and students' ability to grasp mathematical concepts, underscoring its importance in teacher training [13, 14]. Despite the recognized importance of critical thinking and mathematical representation, studies indicate persistent challenges among PESTS in applying higher-order thinking, solving non-routine problems, and utilizing diverse representations [15, 16]. Many rely on procedural approaches rather than conceptual reasoning, limiting their ability to generalize mathematical principles [13]. Difficulties in visual and symbolic representation further impede instructional effectiveness, ultimately affecting students' learning outcomes [8, 17]. Given the direct relationship between teacher competence and student success, addressing these challenges is imperative. Analyzing PESTS' critical thinking and mathematical representation skills—mainly through the lens of cognitive styles offers valuable insights for improving teacher education programs.

Cognitive styles influence how individuals process and structure information, shaping their approach to critical thinking, mathematical representation, and problem-solving [18]. Among these, field-dependent (FD) and field-independent (FI) cognitive styles, as conceptualized by Witkin et al., play a crucial role in mathematics education, particularly in how learners analyze and represent mathematical concepts [19, 20]. Research indicates that FI learners tend to exhibit more excellent analytical skills and flexibility in problem-solving, effectively utilizing diverse mathematical representations. In contrast, FD learners often rely on external references and prior experiences, which can limit their ability to engage with abstract reasoning and construct mathematical representations independently [21, 22]. Recognizing these cognitive differences is essential for designing teacher education programs that accommodate diverse learning needs and develop instructional strategies that enhance both critical thinking and representational proficiency.

Several studies have examined the critical thinking and mathematical representation skills of PESTS, highlighting persistent challenges in these areas. Lee and Lee found that PESTS tend to rely on procedural representations, particularly in fractions, which limits students' conceptual understanding and problem-solving flexibility [23]. Similarly, Saputro et al. demonstrated that problem-based learning enhances critical thinking and self-efficacy, emphasizing the role of instructional strategies in cognitive development [24]. Garderen et al. highlighted the impact of case-based learning on visual representation skills. At the same time, Giancola examined PESTS' mathematical cognitive abilities, reinforcing the importance of critical thinking and problem-solving for effective teaching [25, 26]. Despite these insights, existing studies tend to treat critical thinking and mathematical representation as separate constructs and do not account for how cognitive styles, such as field-dependent (FD) and field-independent (FI), influence these competencies.

Most prior research has focused on instructional strategies for specific mathematical topics but has overlooked broader cognitive factors that shape how PESTS process and apply mathematical knowledge. While FD and FI cognitive styles have been widely studied in general learning contexts, their role in mathematics instruction, particularly in relation to critical thinking and representation skills, remains underexplored. A deeper understanding of these cognitive differences is crucial for designing pedagogical strategies that cater to diverse learner needs. This study addresses this gap by integrating critical thinking, mathematical representation, and cognitive styles, providing a more comprehensive framework for understanding how these factors interact in mathematics education. By bridging these domains, this research contributes to teacher training by emphasizing differentiated instructional strategies that align with varying cognitive preferences. The findings offer practical implications for enhancing representational fluency, improving problem-solving instruction, and fostering adaptive teaching methods.

This study examines the critical thinking skills and mathematical representation of PESTS through the lens of FD and FI cognitive styles. Exploring these relationships seeks to provide insights into the cognitive factors influencing the development of their critical thinking skills and mathematical representations and to propose actionable recommendations for improving teacher training. Specifically, the study is guided by two research questions:

- How do critical thinking skills and mathematical representation manifest in PESTS with an FD cognitive style?
- How do critical thinking skills and mathematical representation manifest in PESTS with an FI cognitive style?

II. RELATED WORK

1. CRITICAL THINKING AS A FOUNDATIONAL SKILL IN MATHEMATICS EDUCATION

Critical thinking is widely recognized as an essential skill in mathematics education, as it enables learners to analyze problems, construct logical arguments, and apply problem-solving strategies effectively [27]. In mathematical contexts, critical thinking involves evaluating information, assessing the validity of mathematical claims, and applying reasoning to justify solutions [28]. For PESTS, developing critical thinking skills is fundamental for their professional competence and their ability to cultivate mathematical reasoning in students [7]. However, research indicates that many PESTS struggle to integrate critical thinking into their teaching practices, often relying on procedural instruction rather than fostering deep conceptual understanding [3]. This limitation becomes particularly evident when they address non-routine mathematical problems that require flexible reasoning and abstraction [29].

The role of critical thinking in mathematics instruction extends beyond problem-solving to include the ability to recognize patterns, evaluate multiple solution strategies, and adapt reasoning processes to different mathematical contexts [3]. A weak foundation in critical thinking can hinder pre-service teachers' instructional effectiveness, limiting their ability to guide students in developing higher-order thinking skills [30, 31]. Consequently, teacher education programs must incorporate targeted interventions to strengthen PESTS' ability to engage students in reasoning-based mathematical activities, moving beyond rote memorization toward deeper cognitive engagement [32].

2. MATHEMATICAL REPRESENTATION AS A KEY COMPETENCY IN MATHEMATICS INSTRUCTION

Mathematical representation constitutes a fundamental competency in mathematics instruction, encompassing symbols, diagrams, graphs, and other visual tools to convey mathematical concepts effectively [33]. Proficiency in representational skills enables students to translate abstract mathematical ideas into concrete forms, thereby enhancing comprehension and facilitating problem-solving [34]. Furthermore, strong representational skills foster logical reasoning, analytical thinking, and creativity, all essential for successful mathematical problem-solving [35].

Several studies highlight the significance of mathematical representation in facilitating students' understanding and mathematical communication. Syah et al. found that external representations, such as diagrams and symbolic expressions, significantly improve students' problem-solving abilities by helping them organize and process mathematical information more effectively [36]. Similarly, Man et al. emphasized that mathematical representation is a cognitive bridge between abstract and concrete thinking, making complex mathematical concepts more accessible to learners [37]. However, these studies only focus on student learning outcomes and do not explicitly address how PESTS develop or use representation strategies for their teaching practice needs.

For PESTS, proficiency in mathematical representation is essential for effective mathematics teaching [12]. Mastery of mathematical representations is crucial for understanding mathematical concepts and solving mathematical problems [38, 39]. Furthermore, representational proficiency has been shown to enhance critical thinking skills integral to mathematical problem-solving [40]. The preference for specific types of representations is also influenced by cognitive styles, shaping PESTS' ability to define mathematical concepts and facilitate student learning [41]. Empirical studies suggest that PESTS with a field-independent (FI) cognitive style employ diverse and flexible representations, enabling them to explore multiple problem-solving strategies. In contrast, field-dependent (FD) group often rely on conventional or procedural representations, which may limit their adaptability in addressing non-routine problems [42]. These cognitive differences indicate that PESTS' capacity to integrate representations in instructional contexts varies, subsequently influencing their effectiveness in fostering students' mathematical understanding.

3. COGNITIVE STYLES AND THEIR IMPACT ON CRITICAL THINKING AND REPRESENTATION SKILLS

The development of critical thinking and mathematical representation skills among PESTS is influenced by their cognitive styles, particularly the distinction between FD and FI styles [43]. Research indicates that individuals with an FI cognitive style tend to excel in mathematical problem-solving due to their analytical abilities and independence in processing abstract information [44]. Sobirin et al. identified significant differences in mathematical representation abilities between FI and FD learners, with the former exhibiting stronger abstract reasoning and more effective use of representations [42]. FI individuals are more adaptable in navigating complex tasks requiring contextual thinking and abstract representation skills [45]. In contrast, FD individuals often rely on external cues and contextual information, limiting their engagement in abstract reasoning and reducing their ability to effectively employ diverse representations [46].

Given these cognitive distinctions, it is imperative to tailor instructional strategies that accommodate varying cognitive styles to optimize learning outcomes for PESTS. Research highlights that FI teachers facilitate higher order thinking more effectively, whereas FD teachers may require structured support to enhance their instructional approaches and representational fluency [21, 47]. Recognizing these differences enables the development of targeted pedagogical strategies that foster critical thinking and mathematical representation skills in teacher education programs [48]. Furthermore, a comprehensive understanding of how cognitive styles influence these competencies can inform curriculum design, ensuring that PESTS acquire adaptive instructional techniques aligned with contemporary educational demands.

III. MATERIAL AND METHOD

This study employed a qualitative descriptive approach to examine participants' experiences, perspectives, and cognitive processes in solving mathematical problems. This approach was selected as it provides a comprehensive and contextually rich understanding of how cognitive styles influence critical thinking and mathematical representation skills insights that may not be fully captured through purely quantitative methods. Furthermore, it enables an in-depth exploration of the reasoning behind problem-solving strategies, rather than merely assessing performance outcomes.

1. PARTICIPANTS

The study was conducted in March 2024 within a pre-service elementary teacher education program in-volving 39 undergraduate students (four males and 35 females) at an Islamic university in Indonesia. The participants were engaged in lessons focused on pedagogical methods for teaching integers and fractions, emphasizing diverse mathematical representations. Six PESTS were selected as primary research informants from the total participants through purposive sampling. The selection criteria considered the diversity of responses, participants' willingness to be interviewed, and their communication skills, which facilitated the data collection process. The six informants were categorized based on cognitive style, with three identified as field-dependent (FD) and three as field-independent (FI). This sampling strategy enabled a comparative analysis of different cognitive approaches and problem-solving strategies.

2. DATA COLLECTION

Data were collected using a combination of cognitive style tests, problem-solving tasks, and semi-structured in-depth interviews. Participants' cognitive styles were determined using the Group Embedded Figures Test (GEFT), adapted from Witkin et al. [43]. The GEFT, administered at the beginning of data collection, classified individuals as FD or FI based on their information-processing preferences. Subsequently, three problem-solving tasks were developed to assess participants' critical thinking skills and proficiency in mathematical representation. Three experts validated these tasks and constructed them using critical thinking indicators adapted from Facione, including interpretation, analysis, inference, evaluation, explanation, and self-regulation [49]. Each task allows participants to go through the stages of critical thinking indicators in the process of reasoning and finding a solution. Following the problem-solving tasks, semi-structured interviews were conducted with the selected in-formants. These interviews explored their thought processes, problem-solving strategies, and mathematical representation techniques in greater detail, focusing on cognitive style differences. The interviews al-lowed researchers to capture the reasoning patterns of FD and FI participants and their reflections on how they adapted their strategies when encountering mathematical challenges.

3. DATA ANALYSIS

Data analysis followed the interactive model proposed by Miles et al., which includes four stages: data presentation, reduction, interpretation, and conclusion drawing [50]. First, qualitative data from problem-solving tasks and interviews were organized into themes reflecting participants' approaches to mathematical reasoning. The data were then reduced by focusing on aspects most relevant to the study's objectives, particularly the characteristics of critical thinking and mathematical representation associated with cognitive styles. During the interpretation stage, thematic analysis was conducted to identify patterns in how FD and FI participants approached the same mathematical problems. For instance, responses were categorized based on whether participants relied on procedural strategies (more common in FD learners) or engaged in abstract reasoning and symbolic representations (more frequent among FI learners). The analysis process also included observations regarding how participants adjusted their approach when faced with difficulties to provide insight into their cognitive flexibility. Finally, conclusions were drawn by triangulating findings across multiple data sources, ensuring the reliability of interpretations. The validity of themes was reinforced through peer debriefing and cross-checking of interview responses with problem-solving performance.

This methodological approach provides a comprehensive understanding of how cognitive styles influence PESTS' critical thinking and mathematical representation skills, offering insights for improving teacher education programs. Despite these rigorous analytical steps, the study acknowledges that interpretations remain context-dependent and subject to researcher bias. Future research could incorporate mixed-method approaches, integrating quantitative measures of cognitive style and problem-solving efficiency to complement qualitative insights.

IV. RESULTS

This section presents the results of an analysis of critical thinking skills and mathematical representation abilities among elementary school pre-service teachers during mathematical problem-solving activities, with a focus on their cognitive styles: FD and FI. Based on the results of a cognitive style assessment, 25 out of 39 participants were categorized as FD, while 14 were identified as FI. From these groups, six informants were selected for in-depth analysis of their critical thinking skills and mathematical representation strategies in the context of mathematical problem-solving. Their performance in solving mathematical problems is summarized in Table 1.

Table 1. The informants' problem-solving performance.

Task	Problem-Solving Results					
	FD Group			FI Group		
	S-01	S-02	S-03	S-04	S-05	S-06
1	False	True	False	True	True	True
2	True	False	False	False	True	False
3	False	False	False	True	False	True

The findings in Table 1 reveal notable differences in the performance of FD and FI informants. PESTS with an FD cognitive style exhibited a higher frequency of errors and were able to correctly solve only one task at most. Importantly, none of the FD informants were successful in solving the third task, which involved more complex problem-solving scenarios, underscoring significant challenges with tasks of higher difficulty. Conversely, FI informants demonstrated greater accuracy and consistency, correctly solving two out of three tasks and showcasing more reliable problem-solving approaches.

1. CRITICAL THINKING AND MATHEMATICAL REPRESENTATIONS USE IN FD GROUPS

Based on the analysis of the problem-solving task sheets and the results of participant interviews, it was found that the PESTS in the FD group demonstrated basic critical thinking skills during the problem-solving process. At the interpretation stage, they attempted to comprehend the problem through diverse approaches. Some informants sought to connect the problem with familiar examples or real-world applications, employing logical analysis as part of their strategy. Others adopted a more iterative approach, rereading the problem statement multiple times to enhance understanding, while a few began solving problems without sufficiently deliberating on accuracy. These tendencies were evident in both their answer sheets and interview responses. The answer sheets provided insights into their problem-solving strategies, with documentation of key elements such as identified variables, contextual frameworks, and step-by-step efforts to derive solutions. FIGURE 1 illustrates these behaviors, highlighting how their interpretation and initial analysis informed their attempts to resolve the tasks.

FIGURE 1 illustrates the problem-solving process undertaken by S-03, an informant from the FD group, in addressing the first problem. The process begins with documenting relevant facts, explaining the problem requirements, and outlining a procedure for solving it. However, a significant limitation was observed during the interpretation phase, where S-03 failed to assess the adequacy of the available data or select a solution strategy suited to the specific challenge. This behavior suggests a tendency among FD informants to prioritize comprehension over accuracy, leading to incomplete or erroneous solutions. These observations highlight a critical gap in the application of advanced critical thinking skills and underscore the necessity of structured strategies for data evaluation and solution accuracy.

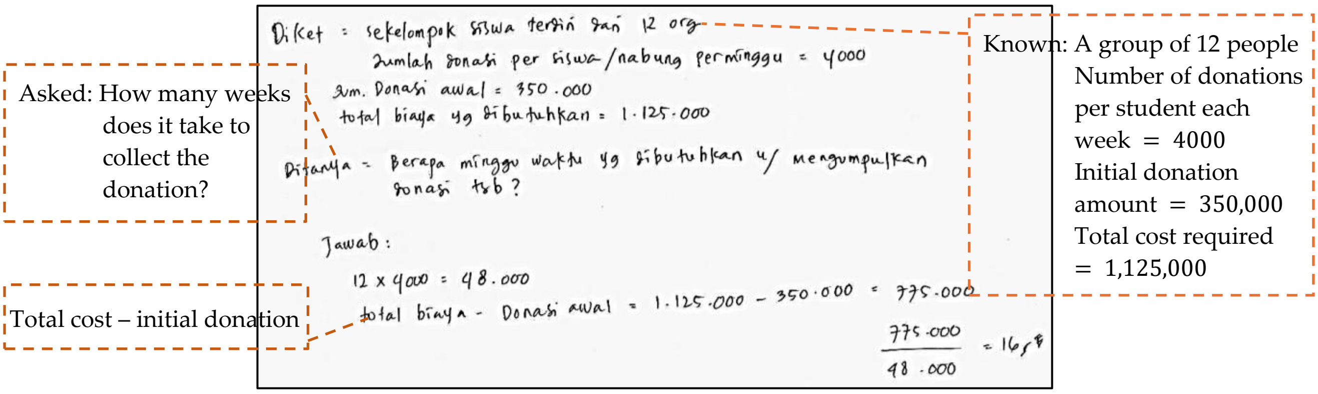

FIGURE 1. The sample of S-03's answer in FD group on the first problem.

During the analysis phase, FD informants demonstrated efforts to investigate the problem by identifying key information and determining the problem's purpose. Informants examined emerging ideas and formulated arguments using diverse strategies. For instance, some relied on prior experiences, while others engaged in independence reasoning to construct their responses. Despite these efforts, FD informants consistently struggled to organize and apply relevant information effectively, often failing to connect the problem's de-tails to the overarching solution objectives. This disconnection points to a need for enhanced analytical competencies to improve problem-solving efficacy.

In the inference phase, inconsistencies were noted in the verification of solutions. For example, S-03 employed a strategy based on prior experience but failed to confirm whether the solution aligned with the problem's requirements, resulting in errors. Verification, a critical component of problem-solving, ensures both the accuracy of the process and the validity of the outcomes. A clear example of this deficiency is shown in Figure 1, where the informant concludes their solution with the calculation 775000/48000 = 16,15 without addressing the specific question posed. The response lacks the necessary further analysis to interpret the calculation and provide a complete solution aligned with the problem's requirements. This failure to link information to the solution objectives highlights weaknesses in inference skills, which are essential for drawing accurate and relevant conclusions. Furthermore, the reliance on prior knowledge without adequate verification indicates broader gaps in both inference and evaluation processes, necessitating targeted interventions to enhance these critical thinking skills.

Furthermore, in the evaluation phase, FD informants showed some effort to assess data adequacy and validate solution strategies based on prior experiences or examples. However, these efforts were inconsistent, and informants rarely revisited or re-evaluated their problem-solving steps. For instance, only one informant reviewed their solution steps for one of the problems, while others relied solely on their initial approach without verifying its correctness. This lack of re-evaluation often stemmed from low confidence in their solutions, as expressed by S-03, who stated, "I rarely verify the solution, as I rely primarily on confidence in my problem-solving process." Such practices underscore the need for systematic evaluation habits to enhance solution accuracy.

In the explanatory category, informants in the FD group approached problem-solving by drawing on similarities to problems they had previously encountered. However, they often failed to articulate final solutions or adequately explain their problem-solving processes clearly. Their reliance on prior experience led to rigidity in determining solution strategies, neglecting verification and the inclusion of a conclusive statement. In-formants claimed their

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approaches aligned with the sample solutions they had studied, reflecting a lack of adaptability in their problem-solving methods.

For the self-regulation phase, FD informants demonstrated careful planning to maintain confidence in their solutions and adjusted strategies when faced with challenges. However, they rarely verified their answers, focusing primarily on managing the problem-solving process rather than ensuring the accuracy of outcomes. This narrow approach frequently resulted in errors, as illustrated in FIGURE 2, highlighting the need for more comprehensive self-regulation practices that integrate verification and reflective evaluation.

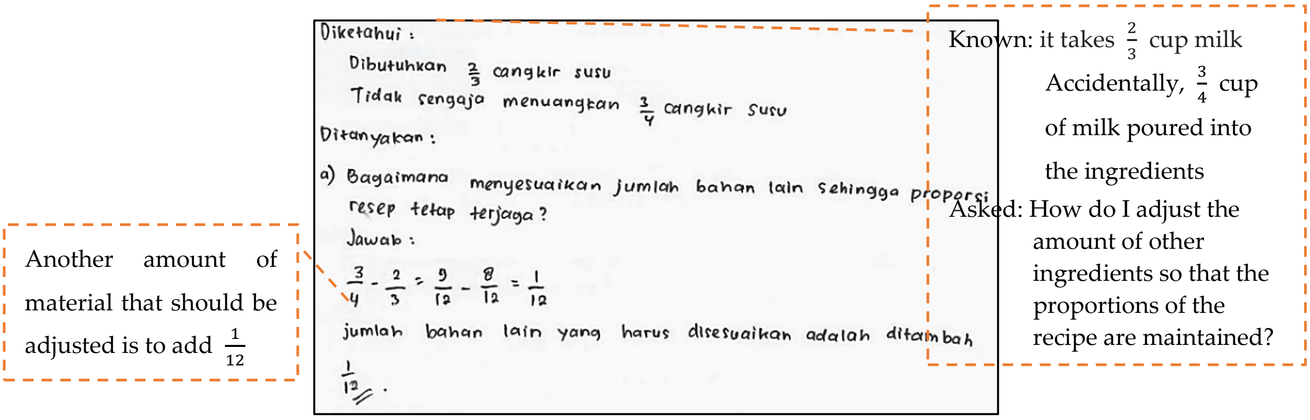

FIGURE 2. The sample of S-02's answer in FD group on the third problem.

FIGURE 2 highlights an error made by S-02 in applying mathematical concepts within their solution strategy. S-02 incorrectly stated that maintaining the recipe's quality required increasing the volume of other ingredients by 1/12 of the dose. This approach is erroneous, as the problem involves proportionality rather than simple addition. The correct strategy requires adding 1/12 of the initial dosage of the other ingredients to preserve proportional consistency.

Regarding mathematical representation skills, the FD group utilized both internal and external representations to support critical thinking during problem-solving. Internal representations were employed to understand the problem, develop solution strategies, and execute the steps to resolve it. External representations, such as mathematical expressions and symbols, were used to communicate solutions effectively. An example of external representation is evident in S-01's work on the second problem, as shown in FIGURE 3.

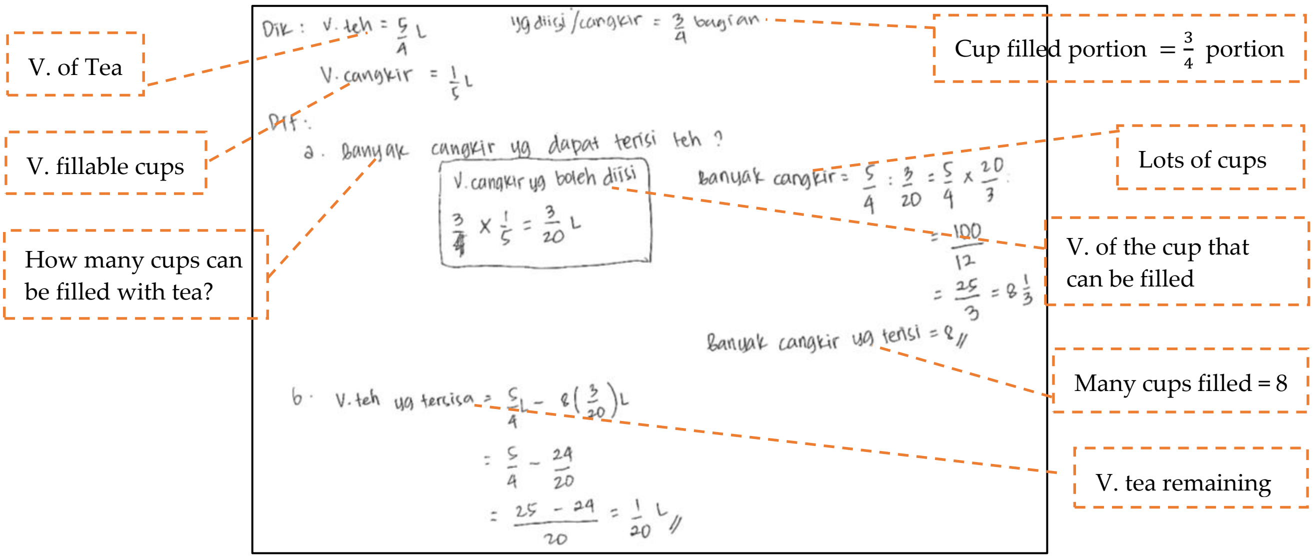

FIGURE 3. S-01's use of mathematical representation in FD group on the second problem.

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FIGURE 3 illustrates the use of external representations by the subjects, including symbols such as "L" for liters and "V" for volume, as well as mathematical expressions incorporating operations like multiplication, division, and subtraction. For instance, a mixed-operation expression, such as 5/4 : 3/20 = 5/4 × 20/3, demonstrates their approach. However, the limited range of external representations used by the FD group constrains their ability to effectively communicate more complex ideas. This finding highlights the need for targeted instruction on diverse mathematical representation techniques to strengthen their problem-solving abilities and deepen their conceptual understanding.

2. CRITICAL THINKING AND MATHEMATICAL REPRESENTATIONS USE IN FI GROUPS

An analysis of the critical thinking characteristics exhibited by informants in the FI group demonstrates a high level of proficiency across all stages. During the interpretation stage, they employed steps such as thoroughly reading the problem to ensure understanding, identifying and categorizing relevant data based on their knowledge and experience, and clarifying the problem's final goal by constructing meaningful connections. In the analysis stage, the FI group exhibited traits such as carefully examining the problem, recording key data, formulating solution strategies, and evaluating arguments to support their approach. They consistently relied on logical reasoning, especially when addressing complex problems, to determine effective strategies. This analytical process is exemplified by the S-05 informant, as illustrated in FIGURE 4.

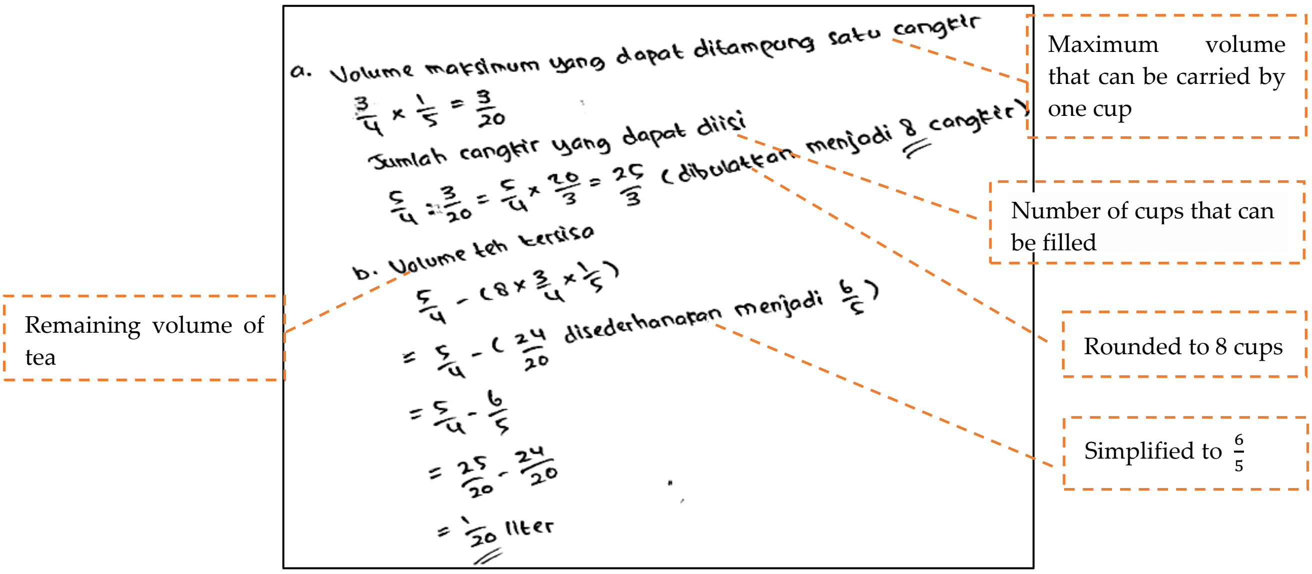

FIGURE 4. The sample of S-05's answer in FI group on the second problem.

FIGURE 4 shows that S-05 demonstrates a non-standard approach to solving the second problem, employing logical reasoning and connecting basic mathematical concepts, such as fractional number operations, to arrive at a structured solution. This process highlights their ability to correlate information with the question, a hallmark of advanced critical thinking, enabling FI informants to consistently tackle complex tasks effectively. Furthermore, In the inference stage, the FI group exhibited traits such as verifying the validity of information, selecting appropriate mathematical concepts, formulating strategies based on those concepts, and cross-checking their answers to align with the problem's objectives. They validated information by linking it to relevant mathematical principles, applying their understanding and knowledge to assess its relevance. These steps ensured that their strategies were both logical and robust.

For the evaluation stage, FI group members ensured their strategies conformed to fundamental mathematical concepts, such as those governing integers and fractions. They assessed the adequacy of the available information by comparing it with the problem's goals and mathematical requirements, and they rechecked their solutions by reviewing each step and concept used. This rigorous evaluation process set the FI group apart, particularly when contrasted with the inconsistencies observed in the FD group. Their ability to validate and refine their strategies underscores their critical thinking strengths.

In the explanatory stage, the FI group demonstrated clarity and precision in presenting their solutions, ensuring alignment with the problem's objectives. They used appropriate mathematical notations, explained their reasoning for chosen strategies, performed accurate solution steps, and employed mathematical expressions to strengthen their arguments. The solution was typically summarized in writing at the conclusion of the process, as shown in FIGURE 5, with notations used to clarify and support the logical flow of their explanation.

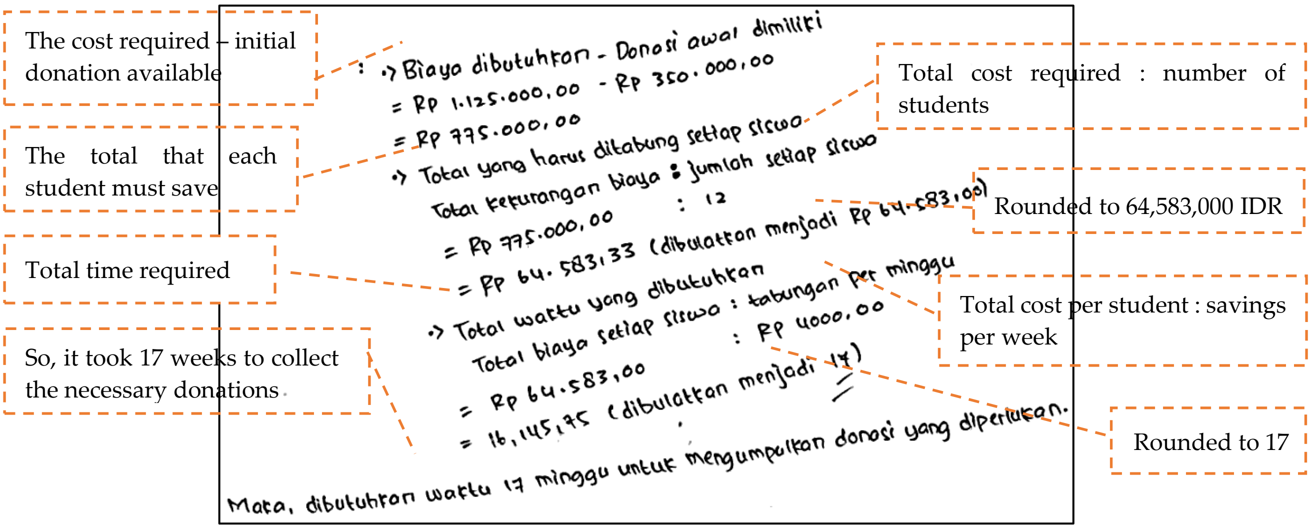

FIGURE 5. The sample of S-04's answer in FI group on the first problem.

In FIGURE 5, S-04 provides a written summary of the solution to the problem, highlighting key steps, particularly those involving number rounding. Furthermore, in the self-regulated category, the FI group demonstrates critical thinking characteristics such as reviewing and revising solution steps, adapting strategies when encountering difficulties, correcting errors, and acknowledging uncertainty when solutions are doubtful. Their self-regulation is most evident in the post-solution verification process, though in some cases, re-evaluation occurs mid-solution when progress stalls. They acknowledge the challenges posed by complex problems, often citing limitations in knowledge, experience, or analysis. This ability to adapt and articulate clear reasoning underscores the FI group's critical thinking strengths.

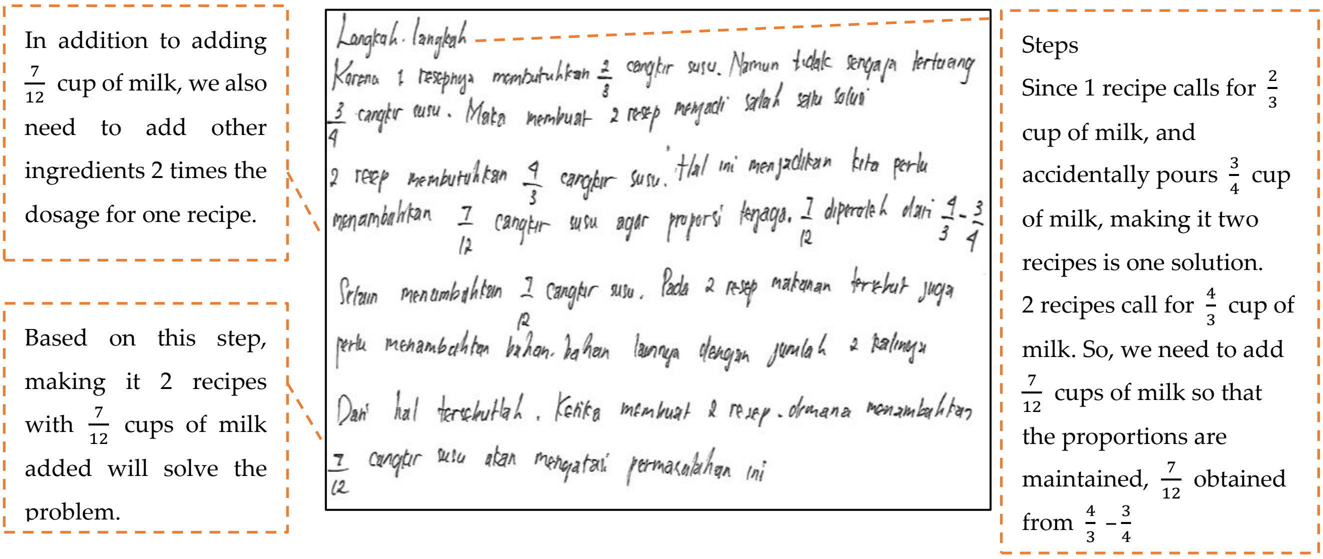

FIGURE 6. S-06's use of mathematical representation in FI group on the third problem.

Regarding mathematical representation skills, the FI group employs both internal and external representations. Internal representations align with the critical thinking stages, such as problem comprehension, idea development, and solution formulation. External representations include mathematical, symbolic, and verbal expressions, with explanatory sentences used to articulate reasoning. An example of their verbal external representation is shown in FIGURE 6, illustrating their ability to combine multiple forms of representation to enhance problem-solving clarity.

In FIGURE 6, S-06 predominantly employs verbal representation in the form of written arguments articulated in their language to solve the third problem. This approach is complemented by the use of mathematical representations, including expressions and notations such as "4/3 – 3/4". The verbal representation serves to clarify the steps and reasoning behind the problem-solving process. The ability of the FI group to seamlessly integrate various forms of representation—verbal, symbolic, and mathematical—demonstrates their deeper comprehension of mathematical concepts and their effective application in solving complex problems.

V. DISCUSSION

1. CRITICAL THINKING AND MATHEMATICAL REPRESENTATIONS USE IN FD GROUPS

The PESTS with an FD cognitive style exhibit limitations in critical thinking across all stages of problem-solving. Their strong reliance on immediately visible information and past experiences hinders their ability to identify relevant data and assess its adequacy. This tendency originates from their cognitive processing style, which prioritizes holistic perception over analytical decomposition, making it difficult for them to isolate key mathematical elements within a problem. Additionally, educational experiences emphasizing rote learning and procedural repetition over conceptual understanding reinforce FD individuals' dependence on external contexts. These characteristics align with the findings of Hasbullah and Sajiman, who highlighted that FD learners often require external cues to structure their problem-solving approach as they struggle with internally driven reasoning [44]. Similarly, studies by Amini et al. and Salwah et al. emphasize that FD learners experience difficulties articulating their reasoning due to their tendency to rely on procedural patterns rather than underlying mathematical principles [51, 52].

The PESTS in the FD group also face difficulties in problem interpretation and analysis. They often adhere rigidly to familiar methods or instructions, limiting their ability to explore alternative or innovative solutions. This challenge stems from their difficulty in restructuring information independently, making them more comfortable following predefined steps rather than adapting to novel situations. Sobirin et al. observed that FD individuals exhibit weaker abstract and independent thinking skills, reducing their problem-solving flexibility [42]. This finding aligns with Sutama et al., who found that FD learners frequently commit errors in problem-solving yet perceive their answers as correct, indicating a lack of self-monitoring and verification processes [53]. As noted by Nasrullah, their dependence on past examples further reinforces this pattern by discouraging the exploration of more generalized or theoretical solutions [54].

In the evaluation stage, FD learners often struggle to critically assess their arguments, consider alternative solutions, or develop flexible problem-solving approaches. Their preference for the first available solution may be linked to cognitive load limitations, as they struggle to manage multiple solution paths simultaneously. Duangngern et al. attributed this tendency to their reliance on social or external validation rather than independent analytical reasoning, making them less likely to question initial conclusions [31]. Additionally, they demonstrate low confidence in finalizing solutions, frequently second-guessing their answers without verifying them. This characteristic is consistent with the findings of Afifah and Ningrum, who reported that FD individuals exhibit weaker critical thinking skills in problem comprehension, planning, and solution verification, which may stem from their reduced metacognitive awareness [55].

One of the factors contributing to these challenges is their limited ability to use mathematical representations effectively. Man et al. stated that the use of multiple Mathematical Representations can overcome one's cognitive limitations in problem solving by facilitating the transition from concrete to abstract reasoning [37]. PESTS in the FD group mostly use simple and direct forms, such as basic symbols and direct mathematical expressions, which limit their ability to engage with abstract mathematical concepts that are important for higher-order thinking. This preference for procedural representations may limit their adaptability in solving non-routine problems, due to their tendency towards conventional problem-solving patterns rather than exploring alternative strategies [42]. They need to master several other varieties of mathematical representations to provide flexibility in problem solving. Goldin emphasized that proficiency in diverse mathematical representations fosters abstract reasoning and deeper cognitive engagement [33]. To support FD learners in overcoming these limitations, structured exposure to external representations—such as diagrams, visual models, and interactive tools—is essential [36]. For example, number lines and bar models help FD learners conceptualize numerical relationships, while graphical representations allow them to visualize functional dependencies in algebraic contexts. By gradually introducing these representational tools, educators can scaffold FD learners' transition from concrete problem-solving to more flexible, abstract reasoning processes.

2. CRITICAL THINKING AND MATHEMATICAL REPRESENTATIONS USE IN FI GROUPS

PESTS with a FI cognitive style demonstrate superior critical thinking skills. They independently identify problem structures and develop sophisticated solutions without relying on external cues or contextual information. This independence aligns with findings by Witkin et al. and Sobirin et al., who noted that FI individuals excel in independent and abstract thinking [42, 43]. During the interpretation and analysis stages, the PESTS in the FI group effectively correlate problem data with mathematical concepts and validate their strategies. This skill set aligns with the findings of Sutama et al., who reported that FI groups are adept at identifying relevant concepts and crafting appropriate solutions [53]. Such abilities are integral to logical reasoning, as highlighted by Kivunja, who emphasized that critical thinking in mathematics involves recognizing patterns and relationships within complex problems [27].

The PESTS in the FI group also excel in inference and evaluation. They systematically assess their reasoning, provide clear and well-structured solutions, and demonstrate consistency in their final answers. Their strong self-regulation is evident in their routine verification of solutions and adjustment of strategies as necessary. Hardiansyah et al. similarly observed that FI groups conduct thorough analyses, present organized problem-solving steps, and achieve accurate outcomes [56]. Their adaptability contrasts with the rigidity observed in FD group and is essential for fostering continuous improvement a critical skill for effective teaching.

One of the key factors contributing to this adaptability is FI learners' proficiency in mathematical representation, which enhances their ability to analyze and communicate mathematical ideas effectively. Budayasa and Juniati highlight that FI individuals not only use mathematical representations efficiently but also employ them as cognitive tools for critical thinking and problem-solving [57]. This aligns with findings from Sobirin et al., who identified significant differences in mathematical representation abilities between FI and FD learners, with FI individuals demonstrating stronger abstract reasoning and more effective use of representations [42]. Mastery of diverse forms of representation enables FI learners to approach problems from multiple perspectives, devise creative strategies, and engage with mathematical concepts at a higher level of complexity [12]. They employ a wide range of representations, including symbolic notations, abstract concepts, and verbal explanations, to deepen their comprehension and refine their solutions, ultimately supporting their ability to navigate complex problem-solving scenarios.

Compared to FD group, the PESTS in the FI group demonstrate a broader and more sophisticated use of mathematical representations. They leverage these skills to identify intricate relationships, design comprehensive problem-solving strategies, and conduct thorough evaluations of their reasoning [19]. Firdaus et al. emphasized that mathematical representations serve as a bridge between abstract and concrete concepts, fostering a deeper understanding of mathematical principles [34]. Through their effective use of internal and external representations, FI group not only achieve deeper mathematical comprehension but also develop instructional approaches that facilitate diverse and effective teaching methods. Table 2 summarizes the key differences between FD and FI groups in terms of critical thinking skills and mathematical representation.

Table 2. Comparison of Critical Thinking and Mathematical Representation Skills PESTS in Groups FD and FI.

Aspect	Field Dependent (FD) PESTS	Field-Independent (FD) PESTS
Interpretation	Rely on explicit and familiar information; struggle to identify relevant details within complex problems.	Identify key concepts independently and establish connections between problem elements.
Analysis	Focus on surface-level details, tend to follow memorized steps rather than deconstruct problems logically.	Break down problems systematically, recognize patterns, and establish logical structures.

Inference	Limited ability to draw logical conclusions; rely on external validation rather than internal reasoning.	Formulate well-reasoned conclusions, use multiple strategies to infer possible solutions.
Evaluation	Struggle to critique solutions, rarely explore alternative problem-solving strategies.	Critically assess problem-solving steps, consider multiple perspectives, and refine strategies.
Explanation	Depend on procedural justifications rather than conceptual reasoning when explaining solutions.	Clearly articulate reasoning processes, justify solutions with logical and conceptual arguments.
Self-regulation	Low confidence, frequent second-guessing, struggle to verify solutions independently.	High confidence, actively self-monitor and adjust strategies as needed.
Mathematical representation	Use basic symbols and direct mathematical expressions, struggle with abstract representations.	Utilize varied representations (symbols, mathematical expressions, and verbal) to enhance problem-solving.

3. IMPLICATIONS OF THE FINDINGS FOR PRE-SERVICE ELEMENTARY TEACHER LEARNING

This research provides valuable insights for designing teacher education programs that equip PESTS with essential competencies in critical thinking and mathematical representation, particularly within the framework of 21st-century learning. The identified disparities between the FD and FI groups highlight the necessity of differentiated instructional strategies that accommodate diverse cognitive styles. Teaching programs should incorporate targeted training to promote adaptive teaching techniques, allowing pre-service teachers to adjust their teaching approaches based on students' cognitive preferences [48].

For PESTS in the FD group, who exhibit a strong reliance on external contexts and limited self-regulatory skills, structured interventions are necessary to enhance critical thinking and problem-solving abilities. Training programs should include specific modules focusing on self-evaluation, inference, explanatory reasoning, and regulatory skills, providing pre-service teachers with structured opportunities to develop these competencies. One effective approach is the integration of inquiry-based learning workshops, where PESTS engage in guided problem-solving exercises that require them to justify their reasoning and explore multiple solution strategies [32]. Additionally, hands-on sessions on mathematical representations such as using diagrams, number lines, and symbolic expressions—can help FD learners develop stronger conceptual connections between concrete and abstract mathematical ideas [37]. Collaborative peer-teaching exercises, where PESTS practice explaining mathematical concepts using various representations, can further enhance their ability to bridge abstract and procedural understanding in classroom instruction [36].

In contrast, PESTS in the FI group, who demonstrate greater independence and proficiency in abstract thinking, require learning opportunities that challenge their cognitive capabilities and refine their instructional adaptability. Advanced training modules focusing on complex problem-solving, metacognitive regulation, and the application of diverse representations in teaching should be incorporated into teacher education curricula. For example, FI learners can benefit from workshops on designing multimodal instructional materials that integrate verbal, symbolic, and visual representations to accommodate diverse student learning styles [12]. Additionally, case-based learning sessions, where pre-service teachers analyze real classroom scenarios and develop instructional strategies tailored to students with different cognitive profiles, can further enhance their pedagogical flexibility [47]. Encouraging FI learners to engage in reflective teaching practices—such as analyzing their own instructional choices and adapting them based on student feedback can also cultivate deeper pedagogical awareness and effectiveness [48].

To ensure that all PESTS are equipped to meet the demands of 21st-century education, it is essential to adopt an adaptive, needs-based curriculum that not only acknowledges cognitive style differences but also provides practical strategies for addressing them in real classroom settings. Such a curriculum should emphasize active learning methodologies, differentiated instruction techniques, and the use of technology-enhanced learning tools to facilitate personalized teaching approaches. As Maharani et al. observed, strengthening critical thinking skills is pivotal for prospective teachers, as it enables them to foster these abilities in their students, ultimately contributing to the overall quality of education and societal progress [29]. By incorporating structured training modules, hands-on workshops, and reflective teaching practices, teacher education programs can better prepare pre-service teachers to navigate the complexities of mathematical instruction and effectively support students with varying cognitive needs.

VI. CONCLUSION

This study explored the critical thinking skills and mathematical representation abilities of PESTS based on their FD and FI cognitive styles within the context of 21st-century learning. The findings highlight distinct cognitive tendencies that shape their strengths and challenges in problem-solving. PESTS, with an FD cognitive style, relied heavily on prior experiences and external references, which hindered their ability to identify key information, verify data, and articulate logical reasoning. Their problem-solving approach often lacked depth, as they focused on procedural calculations without thoroughly evaluating their steps. However, their ability to recognize familiar patterns and apply structured methods suggests that, with appropriate guidance, they could strengthen their conceptual understanding. Their use of mathematical representations remained limited to basic symbolic and numerical forms, restricting engagement with abstract or complex concepts.

Conversely, PESTS with an FI cognitive style demonstrated advanced critical thinking skills and adaptability in problem-solving. They independently analyzed problems from multiple perspectives and employed diverse mathematical representations—including symbols, equations, and verbal explanations to construct well-reasoned solutions. Their ability to relate mathematical concepts and evaluate problem-solving strategies demonstrated a high level of independence and proficiency, reflecting their capacity for abstract and methodical reasoning. Nevertheless, a potential challenge for this group was the tendency to favor abstract reasoning over procedural fluency, which may pose difficulties in scaffolding learning for students with different cognitive styles.

These findings emphasize the need for differentiated instructional strategies that address the specific learning tendencies of FD and FI individuals. Providing structured support for FD learners can enhance their analytical skills and broaden their use of mathematical representations while challenging FI learners with complex; real-world tasks can refine their procedural fluency. By integrating these insights into teacher education programs, this study contributes to the development of inclusive pedagogical strategies that foster adaptive and effective mathematics instruction across diverse learning contexts. Furthermore, this personalized and adaptive learning approach can optimize the educational development of PESTS, equipping them to address the demands of 21st-century education and global challenges.

This study has two notable limitations. The small sample size, drawn from a single university, limits the generalizability of the findings. Additionally, the research design did not fully explore the dynamic interplay between critical thinking, mathematical representation, and cognitive styles, potentially limiting the depth of analysis. Future research should address these gaps by expanding the sample to multiple institutions and incorporating a longitudinal study to examine how PESTS' critical thinking and mathematical representation skills evolve. A mixed-methods approach, combining quantitative assessments with in-depth qualitative analysis, would provide a more comprehensive understanding of these cognitive differences.

Further studies could explore the effectiveness of instructional interventions tailored to FD and FI cognitive styles. For example, experimental research could investigate whether structured guidance improves the analytical skills of FD learners while open-ended, complex problem-solving tasks enhance the adaptability of FI learners. Additionally, classroom-based action research could evaluate how differentiated teaching strategies influence cognitive style groups in real instructional settings. Examining how these approaches impact PESTS' pedagogical practices and student learning outcomes would provide valuable insights for improving mathematics teacher education.

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Author Contributions

Achmad Salido: conceptualization, formal analysis and investigation, writing - original draft preparation, writing - review and editing; Sugiman: data curation, validation; Fery Muhamad Firdaus: data curation; Agung Prihatmojo: supervision, project administration; Agus Herwanto: resources; Eka Yuni Andari: writing - review and editing; Widiya Saputri Wulandari: methodology, resources; Lussy Midani Rizki: methodology, translating manuscript.

Conflicts of Interest

The authors affirm that there are no potential conflicts of interest in the composition of this publication.

Data Availability Statement

The data supporting this study's findings are available from the corresponding author upon reasonable request. Due to privacy and ethical considerations, access to the data is restricted to ensure compliance with applicable regulations. Researchers interested in obtaining the data are encouraged to contact the corresponding author directly.

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