Phenomenon , Tahun 2025, Vol. 15 (No. 1), pp. 131-155
Phenomenon : Jurnal Pendidikan MIPA
phenomenon@walisongo.ac.id

Developing 21st-Century Skills Through Robotics-Enhanced STEM Learning: Effects on Prospective Elementary Teachers' Computational Thinking

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Abstract

Computational thinking has become an essential 21^{st}-century skill, yet prospective elementary school teachers in Indonesia remain underprepared to implement computational thinking in classroom practice. This study aimed to examine the effectiveness of robotics-integrated STEM learning using the PictoBlox platform in improving computational thinking skills among prospective elementary school teachers. A quasi-experimental design with a non-equivalent control group was employed involving 95 fourth-semester Elementary School Teacher Education students selected through purposive sampling. The experimental group participated in robotics-based STEM learning activities including jogging bot design, block-based coding, and Arduino robot programming, while the control group followed conventional learning. Computational thinking was measured using the Computational Thinking Scale with 22 valid items. Mixed ANOVA analysis revealed that the intervention significantly improved problem-solving and critical thinking, while creativity, algorithmic thinking, and cooperativity showed no significant difference between groups. These findings suggest robotics-integrated STEM learning is effective for developing specific computational thinking dimensions and highlight the need for more open-ended challenges, progressive coding modules, and structured cooperative learning to develop other dimensions.

Keywords: STEM education, Robotics, Prospective elementary teacher, Computational thinking.

Mengembangkan Keterampilan Abad Ke-21 Melalui Pembelajaran STEM Berbantuan Robotika: Dampaknya Terhadap Computational Thinking Calon Guru Sekolah Dasar

Abstrak

Computational thinking telah menjadi keterampilan esensial di abad ke-21, namun calon guru sekolah dasar di Indonesia masih kurang siap untuk menerapkan computational thinking dalam praktik pembelajaran di kelas. Studi ini bertujuan untuk menguji efektivitas pembelajaran STEM terintegrasi robotika menggunakan platform PictoBlox dalam meningkatkan keterampilan computational thinking calon guru sekolah dasar. Metode kuasi-eksperimental dengan desain non-equivalent control group digunakan

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ISSN: 2088-7868, e-ISSN 2502–5708

dengan melibatkan 95 mahasiswa semester empat Pendidikan Guru Sekolah Dasar yang dipilih melalui purposive sampling. Kelompok eksperimen berpartisipasi dalam kegiatan pembelajaran STEM berbasis robotika seperti desain robot jogging, pengkodean berbasis blok, dan pemrograman robot Arduino, sedangkan kelompok kontrol mengikuti pembelajaran konvensional. Computational thinking diukur menggunakan computational thinking scale berisi 22 item yang teruji valid. Analisis ANOVA campuran mengungkapkan bahwa intervensi secara signifikan meningkatkan dimensi pemecahan masalah dan berpikir kritis, sedangkan dimensi kreativitas, berpikir algoritmik, dan kerja sama tidak menunjukkan perbedaan signifikan antar kelompok. Temuan ini menunjukkan bahwa pembelajaran STEM yang terintegrasi dengan robotika efektif untuk mengembangkan dimensi berpikir komputasional tertentu dan menyoroti perlunya tantangan yang lebih terbuka, modul pengkodean progresif, dan pembelajaran kooperatif terstruktur untuk mengembangkan dimensi lainnya.

Kata Kunci: Pendidikan STEM, Robotika, Calon guru sekolah dasar, Computational thinking.

INTRODUCTION

Elementary education continues to evolve with increasing attention to the development of computational thinking skills. Computational thinking has become vital for every individual (Ocampo et al., 2024; Papadakis, 2022), encompassing problem decomposition, pattern recognition, abstraction, and algorithm design to solve problems systematically and efficiently (Amri et al., 2022). With the rapid digitalization of various fields, computational thinking is not only essential for tech professionals but also become a basic skill that should be introduced at the elementary school level (Liu et al., 2023).

The Indonesian government recognizes the urgency of developing computational thinking and has integrated it into the elementary Education curriculum (Marifah, 2022) to equip students with computational thinking skills to face future challenges (Kementerian Pendidikan dan Kebudayaan, 2018). However, the implementation of computational thinking in Indonesian elementary schools remains far from optimal. A study on the Bebras Challenge 2023, an international computational thinking competition, found that 87% of Indonesian participants scored below the minimum standard, reflecting the severity of the computational thinking competency gap at the national level (Fitriyah et al., 2024). In the context of teacher readiness, studies by (Abidin et al., 2023; Wahab et al., 2021) revealed that although Indonesian elementary school teachers recognize the importance of computational thinking, the majority still

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ISSN: 2088-7868, e-ISSN 2502–5708

lack sufficient conceptual understanding and practical experience to implement computational thinking meaningfully in their classrooms. This condition is further compounded by the fact that computational thinking integration into the Indonesian curriculum is relatively recent, leaving many teacher education programs still adapting their course structures to adequately prepare prospective teachers for computational thinking-related teaching demands. Although prospective teachers learn about computational thinking in college, they often struggle to apply it in their teaching practice (Sabo et al., 2022).

A preliminary observation conducted at the research site, a teacher education university in Indonesia, revealed that prospective elementary school teachers enrolled in the STEM Education course demonstrated limited familiarity with computational thinking concepts and had minimal prior experience with coding, programming, or robotics-related activities. Most students reported having never engaged in any structured computational thinking-related activities throughout their prior schooling. This condition underscores the urgent need for an instructional approach within the STEM Education course that not only introduces computational thinking conceptually but also provides hands-on, practical experiences to build computational thinking competencies relevant to future classroom teaching.

Therefore, teacher education must provide real-world experiences in implementing computational thinking (Broza et al., 2023). STEM Education courses in elementary schools are a strategic tool for training prospective teachers in developing and implementing computational thinking in elementary schools. STEM education is highly relevant to computational thinking because both emphasize logical thinking, data-driven problem-solving, and technology exploration (Weintrop et al., 2016). Research at various educational levels has even shown that STEM-based learning can enhance computational thinking (Indranuddin et al., 2024; Muharromah M D et al., 2024; Suryani et al., 2024).

One strategy proven effective in enhancing computational thinking in STEM learning is by utilizing educational robotics. Numerous studies have revealed that robotics is an ideal tool for making STEM learning more integrated and practical (Ahmadaliev et al., 2022; Chiazzese et al., 2019; Karaahmetoğlu et al., 2019; Mwangi et al., 2022; Nugraha & Gutami, 2020; Purnomo & Firmansyah, 2021; Shang et al., 2023;

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ISSN: 2088-7868, e-ISSN 2502–5708

Tselegkaridis & Sapounidis, 2022) and can serve as a vehicle for learning computational thinking (Amri et al., 2022; Hsieh et al., 2022). Therefore, prospective elementary school teachers trained through STEM with Educational Robotics (STEM with Educational Robotics) will gain practical experience in implementing computational thinking, equipping them more effectively to teach these skills to their future students.

Although the integration of robotics into STEM learning to enhance computational thinking has been extensively researched, most studies have focused on literature reviews regarding its potential (Chen et al., 2023; Marifah, 2022; Papadakis, 2022; Sundtjønn et al., 2024; Wahab et al., 2021) and its application at the elementary (Cantlon et al., 2024; Shang et al., 2023), secondary (Berk & Gülcü, 2024), and vocational (Amri et al., 2022; Hsieh et al., 2022; Suryani et al., 2024) levels. Meanwhile, computational thinking teaching practices in teacher education remain an under-researched area (Sundtjønn et al., 2024). Existing research is limited to examining teachers' attitudes or perspectives regarding computational thinking (Abidin et al., 2023; Broza et al., 2023). A critical gap therefore exists in the literature, as no study has provided quasi-experimental evidence of the effectiveness of robotics-integrated STEM learning specifically targeting prospective elementary school teachers' computational thinking competencies. Furthermore, most existing robotics-based computational thinking studies have utilized platforms such as Scratch or LEGO Mindstorms, without exploring PictoBlox, a platform that uniquely combines visual block-based coding with direct hardware integration and supports the Indonesian language interface, making it particularly relevant for the Indonesian educational context.

This study proposes novelty by developing a STEM-based lecture strategy with the integration of educational robotics (STEM-ER) specifically assessing its effect on prospective elementary school teachers computational thinking. PictoBlox is a Scratch-based visual block programming platform (Cruz et al., 2021) that supports Indonesian language features and enables the translation of block-based visual coding into C++, which can be directly uploaded to robotics hardware for real-time testing, making it a highly practical and contextually appropriate tool for Indonesian teacher education. Therefore, this study not only plays a role in enhancing the computational thinking skills of prospective teachers but also introduces new tools and methods in teacher

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ISSN: 2088-7868, e-ISSN 2502–5708

education that can be widely adapted and applied. Specifically, this study aims to examine the effectiveness of STEM-ER using PictoBlox in improving computational thinking skills of prospective elementary school teachers across five indicators: problem-solving, critical thinking, creativity, algorithmic thinking, and cooperativity.

RESEARCH METHODS

This study followed a sequential research procedure consisting of five main stages as seen on Figure 1.

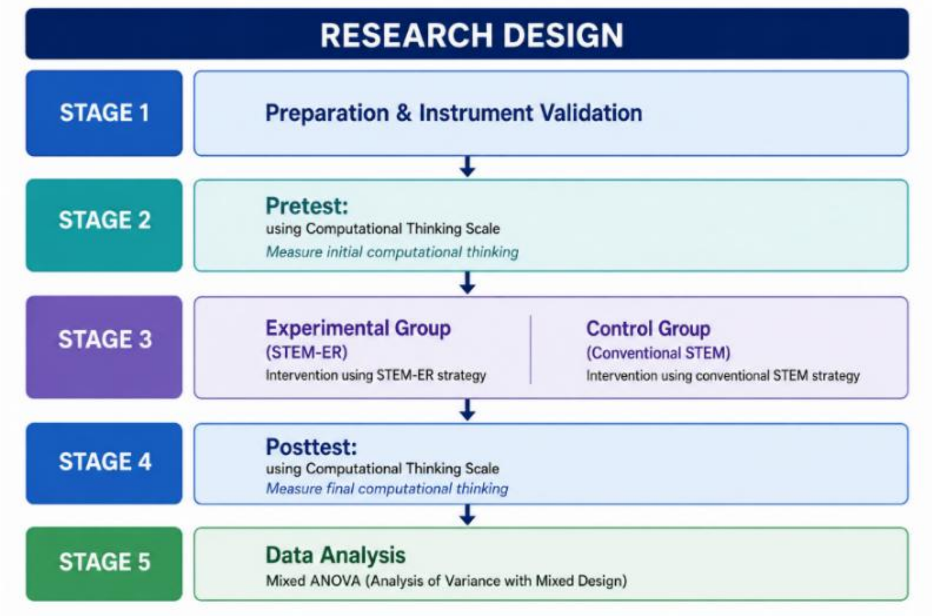

Figure 1. Research design

Figure 1 presents the operational research design of this study that includes (1) preparation, including instrument development and validation; (2) pretest administration to both groups; (3) implementation of the learning treatment across six meetings; (4) posttest administration; and (5) data analysis.

This study used a quasi-experimental method with a non-equivalent control group design, in which two pre-formed classes served as the control and experimental groups. Although there was no internal randomization, the pretest–treatment–posttest structure allowed for evaluation of changes resulting from the treatment (Fraenkel et al., 2012). The control group followed conventional STEM learning that included the delivery of course materials and non-robotics STEM challenge-based practicums. Meanwhile, the experimental group followed STEM learning integrated with robotics elements (Robotics-based STEM Learning), where prospective teacher not only received materials but also carried out STEM challenge-based practicums involving robotics

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ISSN: 2088-7868, e-ISSN 2502–5708

activities. The study was conducted during the even semester of the 2024/2025 academic year at Universitas Pendidikan Indonesia Purwakarta Campus in West Java Indonesia.

Tabel 1. Learning Topics and Activities

Meeting	**Topic**	**Learning Activities**	
		Experiment	**Control**
1	Introduction to STEM Education course	Pre-test	
2	History and Urgency of STEM Education	Analysis of STEM Education Development in Indonesia	
3	STEM Education Components	Building Strong paper tower	
4	STEM Competencies	Making Foil boat	
5	Engineering Design Process	Building Jogging bot	Analysis of EDP in learning process
6	STEM-based learning	Coding with Pictoblox	Exploring STEM-based Learning Kit
7	STEM-based learning	Coding Arduino-based robot	Analyzing STEM-based learning in lower and upper elementary level
8	Mid semester exam	Post-Test	

As it can be seen from Table 1, the treatment was carried out for 3 meetings with details of the materials and practicums as can be seen in the Table 1. Each meeting lasted for 150 minutes. The data collection began with the first meeting, where a pretest was administered to measure initial prospective elementary school teachers' computational thinking in both groups (control and experimental). Subsequently, they attended the next six meetings (meetings 2-7), which discussing topics of: 1) the history and urgency of STEM education; 2) the components of STEM education; 3) STEM competencies encompassing attitudes, knowledge, and skills; 4) the stages of the engineering design process; and 5) examples of STEM-based learning in elementary schools. Following the discussion session and a thorough understanding of the basic material, prospective teacher engaged in group discussions or practical STEM challenge activities. The treatment differences began in meetings 5 to 7, where group activities adapted to a conventional approach and robotics integration. In the control group, prospective elementary teacher engaged in STEM challenges without robotics elements, while in the experimental group, prospective elementary teacher were introduced to basic robotics concepts, coding, and simple programming practices using the PictoBlox application. The robotics-based challenges conducted in the experimental class included activities such as assembling a simple robot through the jogging bot design challenge, coding activities using the Pictoblox app, and programming an Arduino-based robotics device. PictoBlox is a Scratch-based visual block programming platform (Cruz et al., 2021) that has Indonesian language features and can translate block-based visual coding into C++, which is then uploaded to the robot, allowing the program to be tested directly.

After all learning and practical activities were completed, both groups completed the same questionnaire as a posttest to measure changes in computational thinking skills in the eighth session. The same instrument was used as the pretest. Posttest results were also collected through Google Forms.The study population consisted of prospective elementary teacher enrolled in the STEM Learning in Elementary School course at Universitas Pendidikan Indonesia in West Java, Indonesia. Samples were selected through purposive sampling based on two considerations: (1) both classes were taught by the same lecture to minimize instructor variability, and (2) both classes followed the same curriculum structure, ensuring comparability. The sample consisted of two fourth-semester Elementary School Teacher Education (PGSD) classes. The experimental group consisted of 43 prospective elementary school teacher (Class A), while the control group consisted of 52 prospective elementary school teacher (Class B), yielding a total sample of 95 participants.

The computational thinking questionnaire adapted from (Korkmaz et al., 2017) was used as the instrument of this study. The questionnaire is proven to be valid and reliable to be used in teacher education setting (Rodrigues et al., 2024), covering five main indicators: creativity, algorithmic thinking, cooperativity, problem solving, and critical thinking. The questionnaire consisted of 29 statements with response options of strongly agree (5), agree (4), neutral (3), disagree (2), and strongly disagree (1).

Prior to use, the instrument was translated into Bahasa Indonesia. The translated instrument was then piloted on 97 prospective elementary teachers who were not part of the study sample to test its validity and reliability within the Indonesian elementary school teacher education context. Validity testing was conducted using item-total correlation analysis with a minimum r-table threshold of 0.195 (df = 97, $\alpha = 0.05$). Items with a corrected item-total correlation value below the threshold were excluded. The analysis showed that 7 items did not meet the validity criteria, leaving 22 statements valid and suitable for use.

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ISSN: 2088-7868, e-ISSN 2502–5708

Tabel 2. Computational Thinking Indicators and Item Distribution

No	CT Indicator	Definition	Number of Items
1	Creativity	Ability to generate original ideas and innovative solutions to problems	3
2	Algorithmic Thinking	Ability to develop step-by-step logical solutions and understand programming logic	6
3	Cooperativity	Ability to collaborate, share responsibilities, and work effectively in teams	4
4	Critical Thinking	Ability to evaluate information, assess assumptions, and make reasoned judgments	5
5	Problem Solving	Ability to identify, analyze, and resolve problems through structured approaches	4

Table 2 presents the final item distribution of computational thinking indicators used in this study presented. Reliability was assessed using the Cronbach's Alpha coefficient through SPSS 26, yielding a value of 0.831, which is categorized as high (George & Mallery, 2003), confirming that the instrument is reliable for measuring computational thinking skills in the context of Indonesian elementary school teacher education.

Data analysis in this study was conducted to determine the effectiveness of robotics-integrated STEM learning on the computational thinking skills of prospective elementary school teacher. Data were analyzed quantitatively using SPSS 26 software, using an inferential statistical approach in the form of a Mixed ANOVA (Analysis of Variance with Mixed Design). This analysis was chosen because it aligns with the research design, which involved two groups with different treatments (control and experimental), and two measurement times (pretest and posttest). Specifically, Mixed ANOVA was applied separately to each of the five computationa indicators (creativity, algorithmic thinking, cooperativity, critical thinking, and problem solving) to identify which specific dimensions were significantly affected by the STEM-ER intervention

The first step in data analysis was to conduct prerequisite tests (normality and

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ISSN: 2088-7868, e-ISSN 2502–5708

homogeneity). The normality test aimed to ensure that the computational thinking scores in each group were normally distributed, using the Shapiro-Wilk test for the experimental class ($n < 50$) and the Kolmogorov-Smirnov test for the control class ($n > 50$) (Habibzadeh, 2023). Normality was confirmed when the significance value (p) exceeded 0.05. Subsequently, homogeneity of variance was tested using Levene's Test; data were considered homogeneous when $p > 0.05$.

After the data met the basic assumptions, the main analysis was conducted using a Mixed ANOVA. This analysis was conducted to test:

1. Time effects (within-subjects): whether total computational thinking scores changed significantly from pretest to posttest regardless of group
2. Interaction effect (time x group): whether the change in computational thinking scores differed significantly between the experimental and control groups, indicating the treatment effect
3. Group effect (between-subjects), whether the experimental and control groups differed significantly from each other regardless of measurement time

The F value and significance value ($p < 0.05$) were used to determine statistical significance. Effect size was measured using Partial Eta Squared (η^2), interpreted as: small effect ($\eta^2 = 0.01$), medium effect ($\eta^2 = 0.06$), and large effect ($\eta^2 \geq 0.14$) (Richardson, 2011). All data were collected online via Google Forms and processed using SPSS 26.

RESULTS AND DISCUSSION

This study examined the effectiveness of robotics-integrated STEM learning (STEM-ER) on five computational thinking indicators among prospective elementary school teachers. The central finding is that STEM-ER produced a significant and differential improvement specifically in problem-solving and critical thinking, while creativity, algorithmic thinking, and cooperativity showed no significant difference between the experimental and control groups. These results illuminate both the promise and the boundaries of short-term robotics-integrated STEM interventions in teacher education, contributing empirical evidence to a field that has been dominated by attitudinal and conceptual studies rather than experimental designs (Hoz et al., 2024; Sundtjønn et al., 2024).

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ISSN: 2088-7868, e-ISSN 2502–5708

Prior to conducting the Mixed ANOVA analysis, several prerequisite tests were carried out to ensure data validity and the feasibility of using the mixed analysis model. The Shapiro-Wilk test for the experimental class showed $p > 0.05$ (pretest = 0.410; posttest = 0.336), and the Kolmogorov-Smirnov test for the control class showed $p = 0.200$ for both pretest and posttest, confirming normal distribution in both groups. Levene's Test results showed $p = 0.940$ (pretest) and $p = 0.069$ (posttest), confirming homogeneity of variance. The Box's M test yielded a significance value of 0.014, technically indicating that the assumption of equality of covariance matrices was not fully met. However, Mixed ANOVA is relatively robust against violations of this assumption, particularly when group sample sizes are relatively balanced (Pallant, 2020), and the analysis was therefore continued with appropriate interpretive caution.

The Mixed ANOVA analysis was carried out to investigate the impact of robotics-based STEM learning on five indicators of computational thinking skills. The within-subjects analysis reflects whether computational thinking scores changed significantly across time, from pretest to posttest, across both groups combined, independent of the intervention. This captures the general effect of the STEM Education course as a learning experience. The results of the statistical analysis related to the within-subject effect of the time factor can be seen in Table 3.

Table 3. Results of the Within-Subject Analysis of the Time Factor

Indikator	**F**	**Sig.**	**Partial Eta Squared (η^2)**
Creativity	3.656	0.059	0.038
Algorithmic Thinking	5.581	0.000	0.057
Cooperativity	5.732	0.019	0.058
Critical Thinking	12.990	0.001	0.123
Problem Solving	67.228	0.000	0.420

As seen from Table 3, four out of five computational thinking indicators showed statistically significant improvement over time. The problem-solving indicator exhibited the most substantial change, with $F = 67.228$, $p = 0.000$, and a large effect size ($\eta^2 = 0.420$). Critical thinking also showed significant improvement ($F = 12.990$, $p = 0.001$, $\eta^2 = 0.123$, large effect), followed by Cooperativity ($F = 5.732$, $p = 0.019$, $\eta^2 = 0.058$, medium effect) and Algorithmic Thinking ($F = 5.581$, $p = 0.000$, $\eta^2 = 0.057$, medium effect). Creativity was the only indicator that did not show a statistically significant within-subject change (F = 3.656, p = 0.059), suggesting that neither the conventional nor the robotics-based STEM approach provided sufficient creative stimulation to produce measurable gains in this dimension.

These within-subject results indicate that the STEM Education course, comprising challenge-based activities, engineering design process, and collaborative problem-solving tasks, contributed to general computational thinking improvement over time regardless of group assignment. This is consistent with (Budiyanto et al., 2022), who found that educational robotics embedded within STEM teaching produced meaningful computional thinking development through constructivist, hands-on experiences. It also aligns with (Indranuddin et al., 2024; Muharromah M D et al., 2024), who confirmed that STEM-based project learning enhances computational thinking even in the absence of robotics hardware. The absence of significant Creativity improvement across both groups further suggests that task-structured STEM activities — regardless of whether robotics is included — may not naturally stimulate creative thinking without deliberate design of open-ended, generative tasks.

Table 4. Results of Within-subject Interaction Between Time and Group

Indikator	**F**	**Sig.**	**Partial Eta Squared**
Creativity	1.417	0.237	0.015
Algorithmic Thinking	0.293	0.589	0.003
Cooperativity	0.365	0.547	0.004
Critical Thinking	40.147	0.000	0.302
Problem Solving	43.558	0.000	0.319

Table 4 present the results of interaction test between time and group. Results revealed that only critical thinking and problem-solving demonstrated a significant interaction effect. This means that the degree of improvement in these two indicators from pretest to posttest was significantly greater in the experimental group than in the control group, confirming that the STEM-ER intervention, rather than the course in general, was the driving factor behind these gains. Critical thinking showed F = 40.147, p = 0.000, with a large effect size (η^2 = 0.302), while problem-solving showed F = 43.558, p = 0.000, with η^2 = 0.319. Conversely, creativity, algorithmic thinking, and cooperativity showed no significant interaction, indicating that improvements in these indicators did not differ meaningfully between the experimental and control groups.

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The significant interaction effect for problem-solving and critical thinking can be attributed to the progressive and iterative nature of the robotics-based activities in the STEM-ER intervention. Unlike passive or discussion-based learning, hands-on robotics activities inherently demand that learners identify problems, formulate hypotheses, test solutions, and revise designs. These processes are structurally aligned with the core cognitive operations of both problem-solving and critical thinking (Jaipal-Jamani, 2024; Putra et al., 2023). The non-significant interaction for the remaining three computational thinking indicators, by contrast, reflects a structural limitation of the intervention design, where the structured and template-driven nature of the activities constrained opportunities for open-ended creative exploration, deep programming logic engagement, and truly interdependent collaboration. This represents both an important finding and a design limitation of the current study. Between-subject analysis also confirmed previous findings (Table 5).

Table 5. Results of the Between-Subject Analysis

Indicator	F	Sig.	Partial Eta Squared
Creativity	0.002	0.373	0.009
Algorithmic Thinking	0.773	0.381	0.008
Cooperativity	2.085	0.152	0.022
Critical Thinking	38.464	0.000	0.293
Problem Solving	50.950	0.000	0.984

Table 5 showing between-subjects analysis confirmed that the experimental and control groups differed significantly in critical thinking ($F = 38.464$, $p = 0.000$, $\eta^2 = 0.293$) and problem-solving ($F = 50.950$, $p = 0.000$, $\eta^2 = 0.984$). The problem-solving effect size approaching 1.00 reflects an exceptionally large between-group difference, underscoring the powerful and distinctive impact of the STEM-ER intervention on this computational thinking dimension. No significant between-group differences were observed for creativity, algorithmic thinking, or cooperativity.

Table 6. Interpretation of mixed ANOVA results

Computational Thinking Indicator	Change (Time)	Effects of Intervention (Interaction)	Differences among Groups
Creativity	-	-	-

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Computational Thinking Indicator	**Change (Time)**	**Effects of Intervention (Interaction)**	**Differences among Groups**
Algorithmic Thinking	✔	-	-
Cooperativity	✔	-	-
Critical Thinking	✔	✔	✔
Problem Solving	✔	✔	✔

Table 6 summarize key findings of this study which demonstrate that STEM-ER is a pedagogically effective strategy for developing domain-specific computational thinking competencies in prospective elementary school teachers particularly problem-solving and critical thinking. Importantly, this study provides rare quasi-experimental evidence from a teacher education context, extending the predominantly student-focused robotics-computational thinking literature (Cantlon et al., 2024; Shang et al., 2023) into the domain of teacher preparation. Prospective teachers who develop strong problem-solving and critical thinking competencies through STEM-ER are expected to be better equipped to design and implement computational thinking-oriented learning activities in their future elementary classrooms, contributing to the realization of the Indonesian computational thinking curriculum mandate (Kementerian Pendidikan dan Kebudayaan, 2018). This aligns with recent evidence from (Jaipal-Jamani, 2024), who found that robotics-based interventions with pre-service teachers significantly improved science learning and self-efficacy to teach with robotics, and from (Nannim et al., 2024), who demonstrated that project-based Arduino robotics activities significantly enhanced trainee teachers' computational thinking in a programming course.

The significant improvement in problem-solving and critical thinking in the experimental group can be understood through the progressive structure of the STEM-ER learning activities, which systematically engaged prospective teachers in increasingly complex, authentic problem-solving experiences across three key stages: (1) physical robot design through the engineering design process; (2) block-based visual coding using PictoBlox; and (3) hardware-integrated Arduino robot programming. Each stage demanded qualitatively different but complementary cognitive engagement, collectively building a robust foundation for both computational thinking dimensions.

In robotics challenge-based STEM learning, prospective elementary school teachers actively design solutions to real-life problems. For example, in designing a

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ISSN: 2088-7868, e-ISSN 2502–5708

jogging bot.

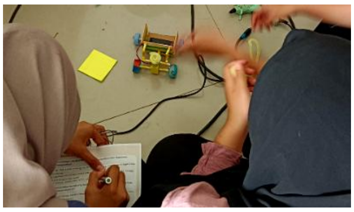

Figure 2. Collaborative work in designing jogging bot prototype

Figure 2 shows prospective elementary school teachers work collaboratively to develop a solution to meet the needs of elders in maintaining fitness through light exercise such as jogging. They must identify user needs, envision a solution, design a robot prototype, and then refine their design — aligned with the Engineering Design Process: Ask, Imagine, Plan, Create, and Improve (Nuraeni, 2023). These stages provide structured opportunities to develop problem-solving skills, as the EDP directly mirrors a six-stage problem-solving model: 1) problem selection and purpose; 2) framing the problem; 3) planning the problem-solving process; 4) interpreting information and selecting a solution; 5) reflecting; and 6) implications and communication of results (Jaipal-Jamani, 2024). In addition, the EDP creates space for critical thinking through evaluating the effectiveness of ideas, questioning assumptions, and revising plans based on empirical trial outcomes (Putra et al., 2023).

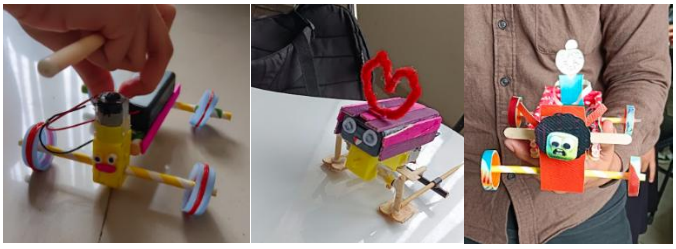

Figure 3. Samples of jogging bot prototype

Figure 3 shows samples of jogging bot prototypes with varied structures and designs. After learning the basics of simple robotics, prospective teacher in experiment group moved to a block-based visual coding practice using the PictoBlox application.

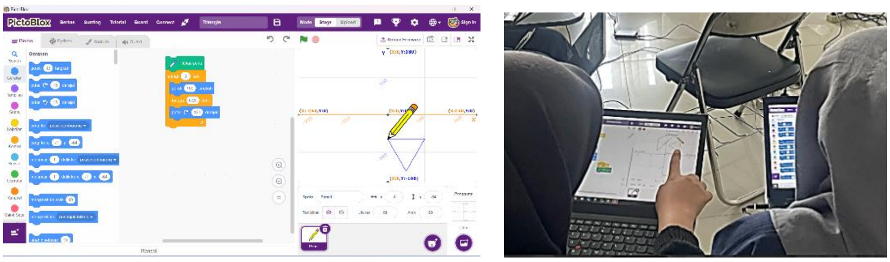

Figure 4. Prospective teacher perform coding in PictoBlox

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ISSN: 2088-7868, e-ISSN 2502–5708

Figure 4 presents prospective teachers activities in building code through PictoBlox app. In this activity, each prospective teacher uses their device to create a series of algorithms to manipulate the motion of digital objects (sprites), such as moving a pencil to form a specific geometric shape, adding sound, and manipulating variables and events. This practice fosters an understanding of computing fundamentals and encourages them to think systematically and develop practical steps to achieve the program's goals.

Such block-based coding activity is closely connected to problem-solving and critical thinking skills. The prospective teacher must be able to recognize the goal (e.g., forming an equilateral triangle), identify the problem (e.g., a sprite not stopping at the correct point), identify possible causes (e.g., the logic of rotation direction or number of steps), and perform debugging. This process mirrors an engineering-based problem-solving model, where prospective teacher continuously generate hypotheses, test, and refine solutions. Using visual programming applications such as Pictoblox enhances critical thinking because preservice teacher must think logically and analyze cause and effect. They are trained to assess the effectiveness of their algorithms and improve them iteratively, which is the essence of critical and reflective thinking. In a study done by (Saritepeci & Yildiz- Durak, 2017) it was found that engaging in a learning process where students generate, evaluate, and revise ideas based on strengths and weaknesses have been demonstrated to enhance their critical thinking skills.

These findings are strongly consistent with (Moraiti et al., 2022) who confirmed that block-based coding activities in educational robotics foster problem-solving, computational thinking, and critical thinking. They are further corroborated by (Budiyanto et al., 2022), who demonstrated through a STEM-robotics intervention that hands-on constructivist robotics experiences produce meaningful computational thinking gains, particularly in problem-solving, by enabling learners to bridge theoretical concepts with practical applications. This study extends these findings specifically to prospective elementary teacher education, a context that has been markedly underrepresented in the empirical literature (Sundtjønn et al., 2024).

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ISSN: 2088-7868, e-ISSN 2502–5708

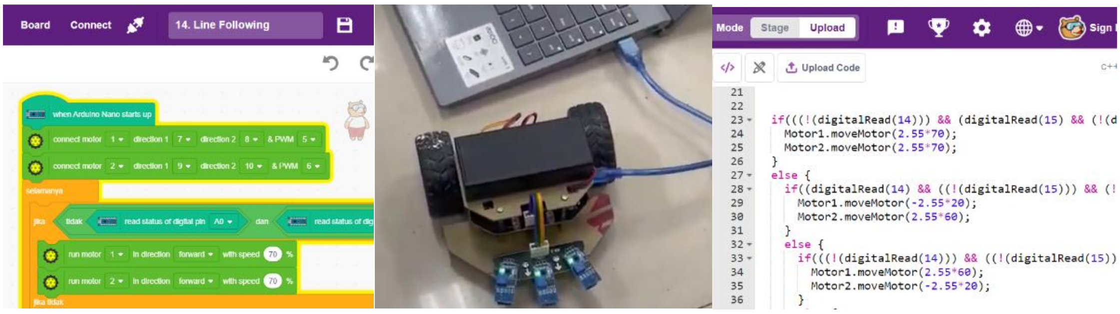

Figure 5. Block-based code sequence transferred to hardware

Figure 5 shows the final stage where prospective teachers programming robots to solve specific challenges, including line-following, obstacle avoidance, and Android-controlled robot tasks. Working in groups, they copied and modified block-based code sequences in PictoBlox transferred to the Arduino Nano microcontroller-based robotics hardware via USB port and observed automatic conversion to C++.

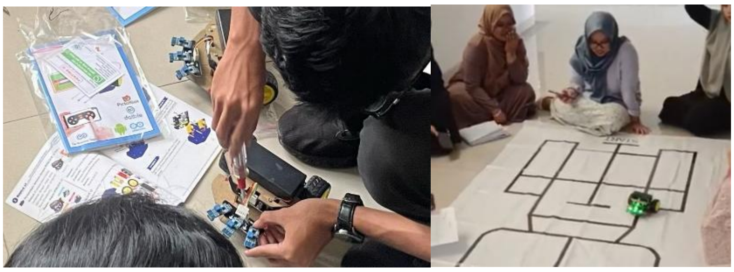

Figure 6. Adjusting sensor sensitivity and testing line follower robot

Figure 6 shows prospective teacher experiment in manipulating several variables, such as the robot's direction of motion, wheel speed, or adjusting particular sensor sensitivity based on testing results. This activity demands technical understanding and challenges the prospective teacher to think critically by analyzing program logic and finding solutions to problems that arise during testing.

The experiences of prospective teachers in the STEM-ER activities described above have demonstrated effectiveness in promoting problem-solving and critical thinking. (Antunes et al., 2023) found that integrating mobile robotics within an active STEM curriculum offers engaging, hands-on experiences that significantly enhance learners' abilities in solving complex problems and thinking critically. Similarly, (Zamora et al., 2025) emphasize that incorporating robotics into project-based and active learning in higher education supports not only technical learning but also broader competencies such as real-world problem-solving. Robotics enables students to manipulate physical components, connect theoretical concepts with practical applications, and engage in authentic problem-solving tasks (Atman Uslu et al., 2023).

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These findings are consistent with results reported by (Hoz et al., 2024) implying challenge-based robotics learning significantly improved their predisposition and self-confidence toward using robotics in teaching that directly linked to problem-solving readiness. (Jaipal-Jamani, 2024) similarly reported that scaffolded robotics interventions with pre-service teachers promoted science learning and problem-solving self-efficacy more effectively than self-guided approaches, highlighting the value of structured, progressive robotics engagement that precisely relevant to the design adopted in this study's STEM-ER intervention. The implication for teacher education is clear: while initial activities such as copying code templates may appear simple, providing prospective teachers with structured space to manipulate variables and iterate on solutions transforms these activities into powerful vehicles for developing higher-order reasoning and analytical decision-making as core components of critical thinking and problem-solving.

Despite the notable gains in problem-solving and critical thinking, other three computational thinking indicators (creativity, algorithmic thinking, and cooperativity) showed no significant differential improvement in the experimental group relative to the control group. Rather than dismissing these as null findings, understanding why these indicators were unaffected is equally important for both theory and practice, as it reveals the boundaries of STEM-ER in its current form and points toward specific instructional refinements needed in future implementations.

Finding shows that creativity did not significantly improve as effect. Although prototype design allows for variation, the activities undertaken focus on technical effectiveness rather than creating truly innovative solutions. Prospective teacher are more directed towards completing tasks that already have a structure or specific objectives such as constructing the same prototype as well as copying coding sequence and only manipulating certain variable. In fact developing creativity in robotics requires a more open and exploratory space, such as open-ended projects that focus more on exploring original ideas than completing technical instructions, on the other hand a standard ready to use platform inhibit creativity (Evripidou et al., 2020).

This finding stands in contrast to studies that reported creativity gains through robotics and coding activities. (Moraiti et al., 2022) found that block-based coding in educational robotics can foster creativity, but only when students are given sufficient

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open-ended design freedom. Similarly, (Anik & Romero, 2024) who examined creative problem-solving using modular cube robotics, found that divergent thinking, a key component of creativity, emerged most significantly when tasks were ill-defined and left open for exploration. The key distinction between those studies and the present one appears to lie in the degree of student autonomy: interventions reporting creativity gains typically employed open-ended, student-directed project designs, whereas the current STEM-ER activities were structured around defined technical objectives. This suggests that future STEM-ER implementations should integrate arts-based and open-ended design challenges to provide the generative, imaginative space that creativity development requires.

Algorithmic Thinking skills require a deep understanding of programming logic, such as loops, conditional statements, and complex algorithm structures. In this study, most coding activities were conducted using provided blocks templates with relatively simple logical interactions, and prospective teachers only exposed to coding and programming activities in two sessions. A study by (Barczak et al., 2023) showed that significant algorithmic thinking development require sustained practice, which may not have been fully addressed in this kind of short intervention.

This finding is consistent with (Wong et al., 2024), who found that meaningful algorithmic thinking development, including debugging and sequencing skills, required sustained, progressive exposure over multiple years of curriculum implementation, not achievable through brief, template-based coding sessions. It also aligns with findings reported by (Wan et al., 2024), who demonstrated that both structuring-oriented and problematization-oriented scaffolding in programming instruction significantly improved computational thinking, including algorithmic thinking, only when implemented across multiple, progressively complex sessions. The two-session coding exposure in this study was likely insufficient for the depth of algorithmic engagement needed to produce significant gains in this dimension. Future implementations of STEM-ER should incorporate a dedicated and progressive coding module spanning a minimum of four to six sessions, with gradually increasing complexity in programming logic structures (from sequential algorithms to conditionals, loops, and sensor-based decision trees) to build genuine algorithmic competence.

In addition, cooperativity also did not significantly improve as effect. Although

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the prospective teachers worked in groups, collaboration was more technical and task-oriented, such as dividing assembly or coding tasks. Deeper collaborative dynamics such as idea negotiation, shared decision-making, and group evaluation were not explicitly facilitated. The literature indicates that developing collaborative skills requires mutual responsibility among individuals, emphasises their interdependence, and ensures a clear understanding of roles and objectives (Evripidou et al., 2020).

This finding is consistent with (Ahmadaliev et al., 2022), who noted that while robotics activities promote student engagement, they do not automatically foster deep collaborative skills unless structured cooperative learning strategies are explicitly embedded in the instructional design. It is further supported by (Shang et al., 2023), who found that robotics STEM camps improved self-efficacy and computational thinking but showed limited effects on collaborative dispositions without deliberate social learning scaffolding. More recently, a systematic review by (Socratous & Ioannou, 2022) confirmed that collaborative skill development in robotics education is significantly enhanced only when role-based structures, shared accountability protocols, and reflective group activities are explicitly designed into the learning sequence. The distinction between technical task-sharing and genuine pedagogical collaboration is therefore critical: the former may produce functional outcomes but is insufficient for developing cooperativity as a computational thinking competency.

Collectively, these findings provide a clear and actionable roadmap for the next generation of STEM-ER interventions. To develop creativity, future implementations should embed open-ended arts-based design challenges within a STEAM framework. To develop algorithmic thinking, a multi-session, scaffolded coding progression should be introduced. To develop cooperativity, structured cooperative learning protocols with assigned roles, shared accountability mechanisms, and group reflection sessions should be explicitly incorporated. The contribution of this study lies not only in confirming the effectiveness of STEM-ER for specific computational thinking dimensions but also in empirically delineating its boundaries, providing a foundation for more comprehensive and theoretically informed computational thinking interventions in Indonesian elementary teacher education programs.

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ISSN: 2088-7868, e-ISSN 2502–5708

CONCLUSION

This study demonstrates that integrating educational robotics into STEM learning (STEM-ER) using the PictoBlox platform significantly improves two key computational thinking indicators (problem-solving and critical thinking) among prospective elementary school teachers as evidenced by large interaction effect sizes ($\eta^2 = 0.319$ and $\eta^2 = 0.302$, respectively), while creativity, algorithmic thinking, and cooperativity showed no significant differential improvement between the experimental and control groups, indicating that the structured and template-driven nature of the current intervention did not provide sufficient conditions for developing these three dimensions. These findings carry important implications for the design of computational thinking-oriented teacher education programs in Indonesia: to address the identified gaps, future STEM-ER implementations should incorporate open-ended, arts-integrated design challenges within a STEAM framework to stimulate creativity; introduce a progressive, multi-session coding module with gradually increasing programming complexity to develop algorithmic thinking; and embed structured cooperative learning protocols (including role assignment, shared accountability, and group reflection) to cultivate cooperativity as a genuine computational thinking competency. Overall, this study contributes empirical evidence from a teacher education context that has been largely absent in the robotics-computational thinking literature, offering a replicable instructional model that can be adapted across elementary teacher education programs to prepare prospective teachers who are not only computational thinking-competent but also pedagogically ready to implement computational thinking-oriented learning in their future elementary classrooms.

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ISSN: 2088-7868, e-ISSN 2502–5708

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