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Research paper

Relationship between Higher-Order Thinking Skills and Computational Thinking in Biology: A STEM-Integrated Perspective on Gender Differences

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ABSTRACT

This study examined the relationship between Computational Thinking Skills (CTS) and Higher-Order Thinking Skills (HOTS) among high school students majoring in biology in Jakarta, Indonesia, using a quantitative, correlational, and cross-sectional research design. Data were collected from 72 students (36 male, 36 female) selected from a population of 144 students through cluster random sampling across all classes, with a stratified procedure within the sampled clusters to achieve a balanced gender composition of 36:36 as an intentional design feature. The CTS test, adapted from the Bebras Computational Thinking Challenge (Blokhuis, 2016), consists of 18 items covering four components: abstraction, algorithm design, decomposition, and evaluation, while the HOTS test, based on the revised Bloom's taxonomy (Anderson & Krathwohl, 2016), consists of 39 multiple-choice questions targeting analysis (C4), evaluation (C5), and creation (C6). Internal consistency in this sample was Cronbach's $\alpha = 0.766$ for the CTS and $\alpha = 0.540$ for the HOTS; the lower HOTS coefficient is discussed as a measurement limitation in Section 5. Overall proficiency was low (CTS = 28.3%; HOTS = 42.2%). Pearson correlations and simple linear regressions showed a significant positive relationship between CTS and HOTS in both subgroups (males: $R = 0.626$, $R^2 = 0.391$; females: $R = 0.709$, $R^2 = 0.503$; both $p < 0.001$). A direct moderation test found that the CTS × gender interaction was not significant ($b = -0.054$, $t = -0.711$, $p = 0.480$; $\Delta R^2 = 0.004$), indicating that the difference in R^2 values does not reflect a significant difference in slope based on gender. Given the cross-sectional nature of this study, the results are interpreted as associative and predictive, not causal; intervention and longitudinal studies are needed.

Keywords: computational thinking skills, higher-order thinking skills, gender differences, STEM education, biology learning

Twenty-first-century challenges across health, environmental, economic, and social domains require systematic, analytical, and creative problem-solving (Archibald et al., 2021; Mazurkiewicz, 2021). Within this framework, Higher-Order Thinking Skills (HOTS), specifically analysis, evaluation, and creation, remain primary educational goals, and Computational Thinking (CT) is increasingly viewed as a cognitive foundation that can support these processes in science education (Pazilah et al., 2024).

CT integrates abstraction, algorithmic reasoning, decomposition, and evaluation, enabling learners to model complex problems and design structured solutions (Kelly & Gero, 2021). Because biology focuses on multivariable processes that are dynamically regulated by hormonal feedback, signal transduction, and immune responses, the

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practices underlying CT are highly aligned with the analytical and evaluative demands that biology places on students, thereby providing a theoretical foundation for simultaneously examining CTS and HOTS in this field (Wu, Asmara, et al., 2024).

Although Indonesia's 2013 Curriculum emphasizes HOTS, student performance on HOTS-oriented biology tasks remains below expectations (Indriani & Zakariyah, 2022). Part of this gap reflects that many educators still lack adequate training in, and conceptual understanding of, the integration of HOTS and computational thinking (Juanda, 2022). The present study addresses an upstream question that precedes intervention design: how strongly students' computational thinking is associated with their higher-order thinking in biology, and whether that association differs by gender (Kasap et al., 2024).

Prior work suggests that CT and HOTS are mutually reinforcing (Hujjatusnaini et al., 2022; H.-Y. Lee et al., 2024), with CT-based instruction linked to stronger analytical and evaluative performance (Lampropoulos et al., 2023; Magno De Jesus & Frango Silveira, 2020). Problem-based, digital (Sulistyanto et al., 2024), and blended environments are common vehicles for integrating CT (Handayani et al., 2022; Verawati et al., 2023) into science instruction (Berk & Gülcü, 2024) Problem-based learning in particular has been shown to help students deconstruct complex scientific problems and build conceptual models of real-world systems (Richardo et al., 2023). When such approaches are combined with STEM-based curricula, the resulting digital learning environments further encourage inquiry-driven, interdisciplinary reasoning and innovation (Xu & Zhou, 2022).

Gender adds a further dimension. Reviews document nuanced differences in engagement (Pratama & Widjajanti, 2024). self-efficacy, and performance in computational contexts (García-Pérez et al., 2025; Kanaki & Kalogiannakis, 2022). Recent evidence from Southeast Asia regarding higher education indicates gender- and role-based differences in students' use of digital tools and generative AI and highlights integrity, validity, and ethics as central to AI-supported STEM education in ASEAN; although these studies focus on higher education rather than secondary-level biology courses, they situate the current discussion on gender and digital learning within the context of recent regional discourse (Khalil et al., 2023; Santosa & Sukmawati, 2023).

Measurement quality is equally important when gender is examined. Because comparisons across subgroups depend on the reliability of the underlying instrument, recent research on validity, reliability, and gender equity in computational thinking assessments (El-Hamamsy et al., 2025) guides how to interpret current instruments and gender-based results. The four-component CT framework used here- abstraction, algorithm design, decomposition (Kelly & Gero, 2021), and evaluation- serves as the operational basis for measurement (Markandan et al., 2022).

This study examines the relationship between CTS and HOTS in high school biology classes, as well as gender differences in this relationship. There are two hypotheses: (H1) CTS has a positive and linear relationship with HOTS; (H2) the strength of this relationship differs between male and female students. In accordance with the cross-sectional research design, these hypotheses are formulated as associative and predictive relationships, not causal ones.

METHODOLOGY

Research design

This study employed a quantitative correlational and cross-sectional design (Creswell & David Creswell, 2018). A correlational survey design was adopted to determine the degree of association between CTS as the independent variable and HOTS as the dependent variable. The study also utilized simple linear regression to predict HOTS scores based on students' CTS performance. Both the Pearson correlation and regression analyses were executed using the Statistical Package for the Social Sciences (SPSS) version 25. This methodological framework was selected to facilitate empirical testing of the hypothesized positive and linear correlation between CTS and HOTS across genders.

Quantitative approaches, such as correlation and regression, are widely used in educational research for examining the interplay between cognitive constructs (Martiana et al., 2022; Maxnun et al., 2024). Correlational analysis offers insight into the magnitude and direction of associations between two continuous variables, while regression enables researchers to estimate the predictive influence of one variable over another. By employing both techniques, the study ensures robust evaluation of the degree to which variations in CTS account for changes in HOTS. This approach aligns with the research objective of elucidating the interdependence between computational and higher-order cognitive abilities in the context of science learning.

Research duration and location

The research was conducted over a two-month period during the 2022/2023 academic year at a senior high school in Jakarta, Indonesia. Jakarta was selected as the research site because it represents a diverse educational environment where disparities in digital access, pedagogical practices, and student learning outcomes can be observed. Conducting the study within a metropolitan context allows for a balanced understanding of both the

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opportunities and challenges in integrating computational thinking into biology education. The two-month duration provided sufficient time for instrument administration, data collection, and verification processes to ensure validity and consistency.

Population and sample

The study population consisted of 144 11th-grade students majoring in science, grouped into whole classes. Sampling was conducted in two stages. First, whole classes (clusters) were randomly selected from the population. Second, within the selected clusters, a stratification procedure based on gender was applied so that the final analytical sample of 72 students had an equal number of male and female participants (36:36). This balanced gender composition was an intentional design feature to facilitate comparisons between subgroups, rather than the result of a single simple random sampling procedure (Widyastuti & Jusra, 2022). The subgroup size of 36 limits the precision of the estimates by gender; this limitation is discussed in Section 5 and forms the basis for conducting the direct moderation test reported in Section 3.7, rather than a comparison of separate R^2 values.

Research variables

Variabel independennya adalah CTS, yang dioperasionalisasikan sebagai abstraksi, perancangan algoritma, dekomposisi, dan evaluasi (Blokhuis, 2016; Wu, Silitonga, et al., 2024). The dependent variable was HOTS, operationalized as analysis, evaluation, and creation(Hujjatusnaini et al., 2022; H.-Y. Lee et al., 2024).

Instruments

Both instruments are explicitly aligned with the 11th-grade biology curriculum in the 2013 Indonesian National Curriculum and are organized into three dynamically structured topics: the Coordination System, the Reproductive System, and the Immune System. These topics were deliberately chosen because each involves dynamic multivariable regulation, hormonal feedback, sequential signaling, and layered defense responses whose requirements align with computational practices, making them well-suited for simultaneously exploring CTS and HOT.

The CTS Instrument. The CTS test was adapted from the UK Bebras Computational Thinking Challenge (Blokhuis, 2016) and consists of 18 questions (ten multiple-choice questions and eight short-answer questions) at three difficulty levels: A (low), B (medium), and C (high). This adaptation involved translating the test into Indonesian and adjusting the context of each question to align with three target biology topics; the adapted questions were then reviewed by subject matter experts to ensure content validity and curricular alignment before being administered to students. In accordance with Bebras scoring conventions, correct answers are awarded positive points and incorrect answers incur a small negative penalty (which varies according to the question's difficulty level); raw scores are then converted into a percentage of the maximum score, so that individual student scores can be either below or above zero, while the group average can still be interpreted as a percentage of maximum performance. The internal consistency for this sample was Cronbach's $\alpha = 0.766$, an acceptable level for research purposes (Nunnally & Bernstein, 1994) (Irwandi et al., 2024; Putri et al., 2022). The four CT components were operationalized as follows:

1. Abstraction: identifying the essential variables of a biological system while ignoring irrelevant detail, for example, representing hormonal feedback in the reproductive and coordination systems as a simplified regulatory model.
2. Algorithm design: ordering logical steps into a valid sequence, for example, mapping the stages of the human immune response during pathogen invasion.
3. Decomposition: breaking a complex structure into manageable parts, for example, separating the nervous system into components and their specific microfunctions.
4. Evaluation: judging the efficiency or accuracy of a proposed solution within a biological context.

The HOTS test is based on the revised Bloom's Taxonomy by Anderson & Krathwohl (2016) , targeting, analysis (C4), evaluation (C5), and creation (C6). This questionnaire consists of 39 multiple-choice items scored dichotomously (1 = correct, 0 = incorrect), which were then converted into percentages. The internal consistency for this sample was Cronbach's $\alpha = 0.540$. This value is lower than the conventional threshold of 0.70, partly because the dichotomous scoring of the 39 items, which exhibited a significant floor effect (mean = 42.2%), reduced item variance and inter-item covariance. Report these coefficients transparently (Yennita & Zukmadini, 2021), discuss them as measurement limitations in Section 5, and align our interpretation with the recommendations of El-Hamamsy et al. (2025) that CT-related assessments need to be critically examined regarding reliability and gender-fair functionality (Putri et al., 2023 ;Masrifah et al., 2025). In addition to reliability, validated CTS and HOTS instruments generally include creativity-oriented indicators, such as fluency, flexibility,

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originality, and elaboration, which are consistent with established frameworks for creative and critical thinking (Yennita & Zukmadini, 2021).

The distribution of the 57 items across the three biology topics and the CTS and HOTS indicators is presented in **Table 1**.

Table 1

Distribution of items across biology topics and cognitive indicators

Instrument / Indicator	Coordination	Reproductive	Immune	Total
CTS – Abstraction	2	2	1	5
CTS–Algorithm design	1	1	2	4
CTS– Decomposition	2	1	1	4
CTS–Evaluation	1	2	2	5
HOTS–Analyse (C4)	5	4	4	13
HOTS–Evaluate (C5)	4	4	5	13
HOTS–Create (C6)	4	5	4	13
Total	19	19	19	57

Note: item counts illustrate the operational blueprint; authors should reconcile per-cell counts with the final answer key before typesetting (added).

Data Analysis

The analysis combined descriptive statistics (mean, standard deviation) with inferential procedures. Pearson's correlation and simple linear regression were used to test H1 (the relationship between CTS and HOTS) within each gender subgroup (Martiana et al., 2022; Maxnun et al., 2024). Prior to the inferential tests, the assumptions of parametric regression were verified: normality via the Kolmogorov–Smirnov test; linearity via an examination of the CTS–HOTS scatterplot; independence of residuals via the Durbin–Watson statistic; and homoscedasticity via an examination of the standardized residual plot. When ANOVA rows are reported in the regression results, this indicates the statistical significance of the regression model, not a comparison of group means.

H2 (whether the strength of the CTS–HOTS relationship differs by gender) was tested directly using a moderated regression model. CTS was centered to reduce multicollinearity, and HOTS was regressed on the centered CTS, gender (0 = male, 1 = female), and the CTS × gender interaction term. A statistically significant interaction indicates that the CTS–HOTS slope differs across subgroups; a non-significant interaction implies that any numerical difference between the separately estimated R^2 values of the subgroups should be interpreted descriptively, rather than as a gender effect.

Ethical considerations

This study was conducted in accordance with applicable research ethics principles. Ethical approval and official research permission were obtained from the Graduate School of Muhammadiyah University Prof. DR. HAMKA through an official request/approval letter No. 102/C.01.08/2023 dated January 25, 2023. This study was conducted at State Senior High School 65 Jakarta on February 2, 2023. All participants and the school provided informed consent before data collection began, and participation was voluntary. Data confidentiality and participant anonymity were strictly maintained in accordance with personal data protection regulations and academic ethical standards.

RESULT

Overview of results

The analysis, conducted using SPSS version 25, included descriptive statistics, tests of normality and assumptions, Pearson's correlation, simple linear regression for each gender subgroup, and a CTS × gender moderation test. These findings were interpreted within the framework of a cross-sectional study design.

Descriptive statistics

Overall, students' CTS was low (M = 28.31%, SD = 27.77), and their HOTS was also low (M = 42.20%, SD = 11.33). Subgroup descriptives were similar for the two genders: male students scored M = 29.19 (SD = 29.65) on CTS and M = 42.88 (SD = 13.62) on HOTS; female students scored M = 27.44 (SD = 26.15) on CTS and M = 41.53 (SD = 8.61) on HOTS (**Table 2**).

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Table 2

Descriptive statistics of CTS and HOTS by gender (added)

Group	CTS Mean (%)	CTS SD	HOTS Mean (%)	HOTS SD	N
Male	29.19	29.65	42.88	13.62	36
Female	27.44	26.15	41.53	8.61	36
Overall	28.31	27.77	42.20	11.33	72

At the component level, students scored highest on abstraction (39.5%) and evaluation (33.9%) in CTS, and lowest on decomposition (25.0%) and algorithmic reasoning (23.7%); in HOTS, they scored highest on creation (45.8%) and analysis (44.8%), and lowest on evaluation (31.1%). The fact that abstraction is the strongest component of CTS is consistent with research showing that abstraction helps students identify relevant variables and generalize patterns in scientific phenomena (Christensen, 2025). The relatively weak evaluative performance is consistent with reports that evaluative thinking, which requires metacognitive reflection and evidence-based assessment, is often underemphasized in traditional classrooms (Kania et al., 2024; Mukti et al., 2023), and the generally low levels of HOTS are consistent with international findings that only a small proportion of students reach advanced levels in analysis, evaluation, and creation (Maryani et al., 2022; Sidiq et al., 2021). Gender differences at the component level were relatively small and not statistically significant (**Figures 1** and **2**).

Figure 1

Average percentage of computational thinking skills (CTS) components by gender (n = 72)

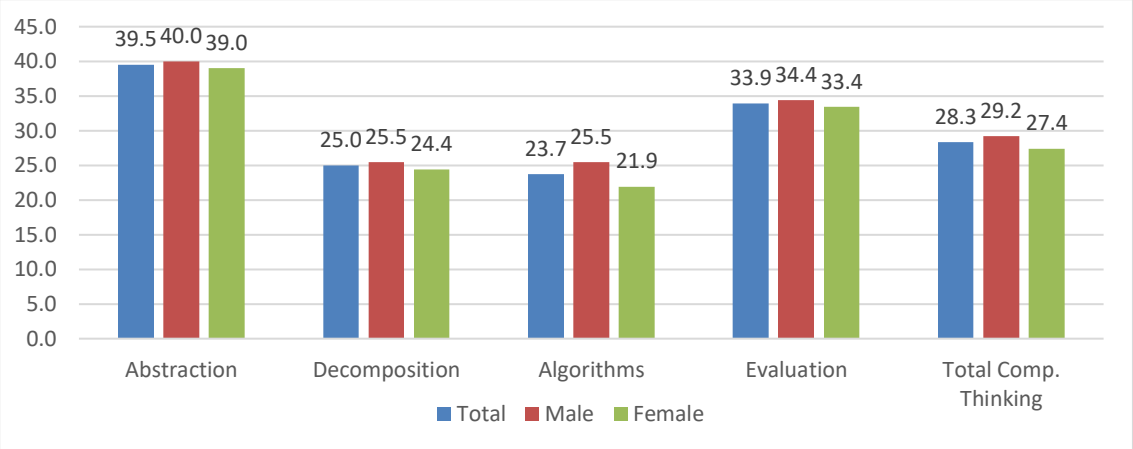
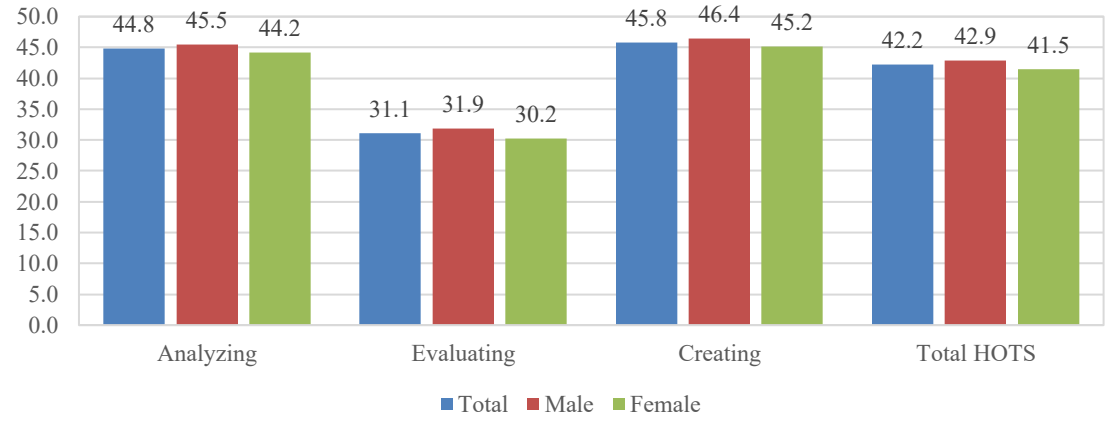


Figure 2

Distribution of higher-order thinking skills (HOTS) indicators by gender (n = 72)



Assumption checks

The Kolmogorov–Smirnov test indicated a normal distribution for both groups (men: statistic = 0.101, p = 0.200; women: statistic = 0.096, p = 0.200). Scatter plots support linearity; the Durbin–Watson statistic was 1.500 for the male model and 1.508 for the female model, both of which fall within the acceptable range (approximately 1.5–2.5) and support the independence of the residuals; the plot of standardized residuals shows no obvious heteroscedasticity. Overall, this examination justifies the use of Pearson's correlation and linear regression.

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Table 3

Kolmogorov–Smirnov normality test results (male students)

Group	K–S statistic	p (2-tailed)	Durbin–Watson	Decision
Male (n = 36)	0.101	.200	1.500	Normal; independent
Female (n = 36)	0.096	.200	1.508	Normal; independent

Regression (male students)

For male students, the regression model was statistically significant, $F(1, 34) = 21.867$, $p < 0.001$. The equation is HOTS = 34.499 + 0.287 × CTS, with $R = 0.626$ and $R^2 = 0.391$, indicating that 39.1% of the variance in HOTS is associated with CTS in **Tables 4–5**.

Table 4

ANOVa male subgroup regression

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2538.873	1	2538.873	21.867	000[b]
	Residual	3947.637	34	116.107		
	Total	6486.510	35			

Table 5

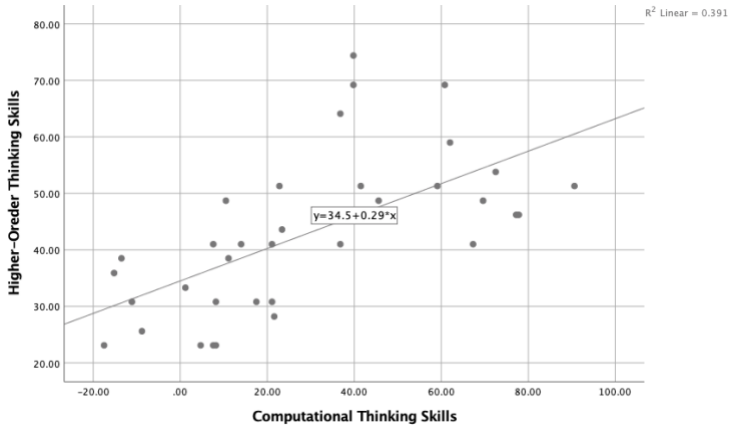
Coefficients coefficients male subgroup

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	34.499	2.538		13.594	.000
	Computational thinking skills	.287	.061	.626	4.676	.000

R = 0.626	$R^2 = 0.391$	adj. $R^2 = 0.374$	SEE = 10.775	DW = 1.500

Figure 3

Regression equation visualization for male students (CTS–HOTS relationship)



An R^2 value of 0.391, although considered moderate, reflects a meaningful level of predictive power; R^2 values between 0.35 and 0.50 indicate a substantial cognitive relationship. These results support the theoretical claim that computational practices such as abstraction and algorithm design form the foundation of the analytical and evaluative reasoning processes underlying HOTS.

Regression and correlation analysis (female students)

For female students, this model was also significant, $F(1, 34) = 34.461$, $p < 0.001$, with HOTS = 35.123 + 0.233 × CTS, $R = 0.709$, and $R^2 = 0.503$ (Tables 6–7). The numerically higher R^2 value for the female group is reported here descriptively; whether the CTS–HOTS slope differs significantly by gender is tested directly in the next section.

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Table 6

ANOVA female subgroup regression

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1304.868	1	1304.868	34.461	000[b]
	Residual	1287.405	34	37.865		
	Total	2592.272	35			

a. Dependent Variable: Higher-order thinking skills

b. Predictors: (Constant), Computational thinking skills

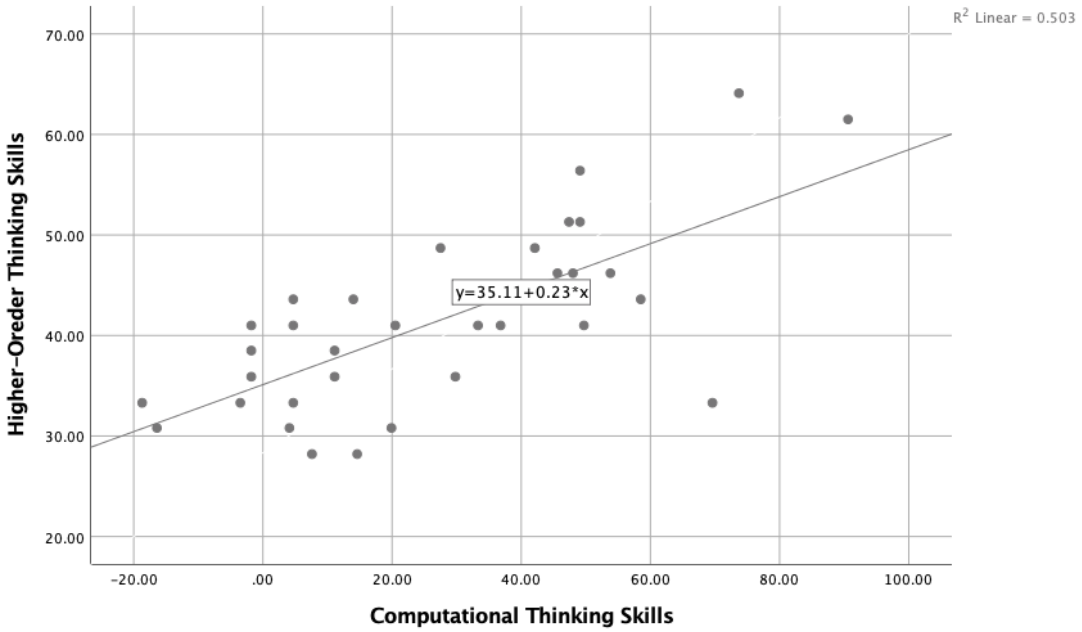
Table 7

Regression coefficients (female)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	35.123	1.497		23.457	.000
	Computational Thinking Skills	.233	.040	.709	5.870	.000
R = 0.709	R^2 = 0.503	adj. R^2 = 0.489		SEE = 6.153		DW = 1.508

Figure 4

Regression equation visualization for female students (CTS-HOTS relationship)



Direct test of the gender difference (moderation)

In a direct test of H2, HOTS was regressed against CTS (centered on the mean), gender (0 = male, 1 = female), and the CTS × gender interaction. The overall model proved significant, $F(3, 68) = 16.79$, $p < 0.001$, $R^2 = 0.426$, confirming that CTS can predict HOTS in the combined sample. Most importantly, the interaction term was not statistically significant, $b = -0.054$, $SE = 0.076$, $t = -0.711$, $p = 0.480$, and its unique contribution was negligible ($\Delta R^2 = 0.004$; F-change $(1, 68) = 0.505$, $p = 0.480$). The main effect of gender was also not significant ($b = -0.897$, $t = -0.434$, $p = 0.666$) (**Table 8**).

Table 8

Moderated regression: HOTS on centred CTS, gender, and their interaction

Predictor	B	SE(B)	t	Sig.
(Constant)	42.630	1.463	29.139	.000
CTS (centred)	.287	.050	5.743	.000
Gender (F = 1)	−.897	2.069	−.434	.666
R^2 = 0.426	ΔR^2 for interaction = 0.004		F-change(1, 68) = 0.505	p = .480

Interpretation. Since the CTS × gender interaction was not significant, the numerical differences between the coefficients for the male subgroup ($R^2 = 0.391$) and the female subgroup ($R^2 = 0.503$) do not reflect statistically

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reliable differences in the CTS–HOTS slope based on gender. The simple slopes estimated from the moderation model were 0.287 for males and 0.233 for females, and the difference in slopes ($b = -0.054$) remained within the bounds of sample variability. Therefore, H2 is not supported: the strength of the CTS–HOTS relationship does not differ significantly between male and female students in this sample. These findings are consistent with meta-analysis reports indicating that gender differences in computational and higher-order thinking skills tend to diminish or disappear under equivalent learning conditions (Santosa & Sukmawati, 2023; D. Sun et al., 2023).

H1 is supported: CTS has a significant and positive relationship with HOTS in both gender subgroups and in the combined sample. H2 is not supported: the CTS × gender interaction is not significant, so the CTS–HOTS relationship does not differ significantly by gender. Overall, these results are consistent with the conceptual relationship between computational reasoning and higher-order thinking skills (Gilchrist et al., 2021; Markandan et al., 2022), though they remain within the associative limitations of a cross-sectional design.

DISCUSSION

Both CTS (28.3%) and HOTS (42.2%) fell below the expected proficiency level, consistent with findings that developing computational and higher-order thinking skills is challenging in resource-constrained environments (Polat et al., 2021; Roa González et al., 2025). Summarizing what appears to be a repetition in the original draft, three interrelated factors seem to account for these low proficiency levels: uneven teacher readiness in implementing HOTS-oriented pedagogy (Kong & Lai, 2023; Resnick, 2023); limited access to digital tools and computational tasks (Celik et al., 2023; Yan & Pourdavood, 2024); and sociocultural inequities in prior exposure to STEM problem-solving (Osman & Kriek, 2021). These conditions are important because the development of both CTS and HOTS depends on learning environments that intentionally integrate critical thinking, creativity, and computational reasoning (Danial et al., 2021), and because disparities in technology infrastructure and readiness among schools directly contribute to the observed deficits (Tsybenko et al., 2023). Particularly in schools with limited resources and inadequate infrastructure, digital literacy resources limit students' opportunities to engage in computational and higher-order thinking activities (Yan & Pourdavood, 2024). Technology-supported constructivist professional development, including approaches such as CASE and project-based learning, has been linked to better student learning outcomes (Franco & Vieira, 2019; Oliver & Venville, 2017).

Teacher competence and curriculum implementation also play a central role (Al-Hinai et al., 2026). Educators play a vital role in facilitating the reflective process; through this process, students learn to analyze, evaluate, and create knowledge (Kosasih et al., 2022; Tatang et al., 2023). However, limited professional and technological competencies can cause traditional didactic approaches to remain dominant, and hinder both analytical and creative reasoning (Alotaibi, 2023). Therefore, continuous, constructivist, and technology-supported professional development is associated with better computational and cognitive outcomes for students (Afikah et al., 2023; Darhim et al., 2020).

Male and female students did not show significant differences in either CTS or HOTS, and a direct moderation test indicated that the CTS–HOTS slope also did not differ significantly by gender (interaction $p = 0.480$, $\Delta R^2 = 0.004$). The numerical difference in subgroup R^2 values (0.503 vs. 0.391) reflects sample variability at $n = 36$ per group, rather than a strong gender effect. This refines the initial theoretical framework of this study and aligns with recent evidence that gender differences in computational and cognitive performance narrow or disappear under equivalent learning conditions (Santosa & Sukmawati, 2023; D. Sun et al., 2023), as well as with regional research on gender-based digital engagement in STEM education in Southeast Asia (Raza et al., 2025).

Context-dependent gender variations tend to stem from contextual factors such as access to learning resources, teaching styles, and cultural norms, rather than from ability (Demir-Kaymak et al., 2021), and structural inequalities in prior exposure may result in some female students having more limited access to digital tools and support in STEM fields (González-Pizarro et al., 2024). Consistent with this, gender-based perceptions of technical expertise—rather than ability appear to drive differences in engagement (Ryzhanina & Tarasova, 2025; Serrano et al., 2024). Whereas differences between male and female students are sometimes described as male students demonstrating stronger algorithmic self-confidence, while female students demonstrate strong metacognitive awareness and collaborative tendencies that support the creative and analytical aspects of HOTS (Väätäjä & Ruokamo, 2021), as well as patterns in which male students excel in analytical or evaluative tasks, while female students perform equally well or better on creative and organizational tasks (Mat et al., 2023; Shian & Rosli, 2024). Research does not support the assumption that these differences are fixed; these small and non-significant differences reinforce the argument that gender does not inherently determine cognitive capacity under equivalent conditions (Lu et al., 2021), and this strengthens the case for gender-inclusive practices, including attention to students' beliefs regarding expectations and values in STEM learning (Saw et al., 2025), so that both groups achieve comparable performance (Blancia et al., 2024; Lasfeto et al., 2024). Collaborative and inclusive computing activities, such as robotics programs designed for equal participation, have been shown to enhance engagement and self-confidence among female students in particular (Ardito et al., 2020; Richardo et al., 2023).

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Regression and moderation results support a meaningful, gender-independent relationship between CTS and HOTS, rather than a causal mechanism. Students with stronger abilities in abstraction, algorithm design, and decomposition tend to demonstrate stronger analytical, evaluative, and creative reasoning, in line with Bloom's revised taxonomy (A. S. Putri et al., 2023) and the view that CT serves as a cognitive framework for higher-order thinking (Kules, 2016; Robledo-Castro et al., 2023). Related STEM studies also report that computational thinking proficiency predicts students' higher-order reasoning and is meaningfully integrated with broader STEM competencies (Han et al., 2024; Yang et al., 2024).

These reflective and self-monitoring capacities, which involve evaluating alternative solutions and regulating one's own thinking, constitute the cornerstone of HOTS (Hooshyar et al., 2019), and the integration of computational thinking into STEM is believed to foster analytical and creative skills, leading to deeper learning (Alimisis, 2021).

Constructivist and technology-based PBL environments, game-based tasks, simulations, and robotics are associated with stronger engagement and reasoning (Chen & Hui, 2024; Hong et al., 2021; Qu & Fok, 2022), and exposure to computational methods such as simulation modeling and data interpretation can build the analytical resilience that underlies science literacy (Zhu et al., 2023). Learning analytics can further help teachers monitor progress and tailor support (Celik et al., 2023), and integrating these practices into a sustainable, integrated STEM education model can help these outcomes endure over time (J. Han et al., 2023). Realizing these values in practice depends on teacher training that integrates the principles of computational learning as well as adaptive and accessible educational technology (Friskawati & Supriadi, 2022; Omeh et al., 2025), as well as addressing the disparities in infrastructure and teacher readiness still found in many schools in Indonesia (Prahmana et al., 2024). These observations are encouraging but do not prove the value of integrating CT into biology instruction; evidence from interventions is needed to move from association to impact.

Practical recommendations for the biology classroom

The following low-cost activities can be incorporated into existing class periods to reinforce the four components of CT in biology:

a. Writing algorithms for immune responses: Students create a list of sequential steps in the human immune response to pathogens, then test that sequence based on case scenarios.
b. Breaking down the nervous system: Students divide the nervous system into its components and explain each micro-function before reassembling the entire system.
c. Abstraction of hormonal feedback loops: Students reduce hormonal feedback loops to their essential variables and depict them as simple input–process–output models.
d. Brief evaluation questions: Students evaluate two proposed solutions to a biological problem based on accuracy and efficiency, and justify their choices by focusing on the weakest observed indicator (evaluation).

LIMITATIONS

Several limitations should be noted when interpreting these findings.

1. The sample was small and drawn from a single school in a single city, which limits the ability to generalize to other schools, regions, and curricula.
2. The cross-sectional and correlational study design does not allow for causal claims; the observed relationship does not prove that CTS reinforcement leads to an increase in HOTS.
3. Each gender subgroup consisted of only 36 students, so subgroup coefficients were estimated with limited precision. Therefore, comparisons by gender are based on moderation tests, rather than on separate numerical comparisons of R^2 values.
4. The internal consistency of the HOTS instrument in this sample (Cronbach's $\alpha = 0.540$) falls below the conventional threshold of 0.70, reflecting the combined effects of dichotomous scoring, a broad content coverage design spanning three biology topics, and a floor effect. Therefore, results involving HOTS should be interpreted with caution, and instrument refinement is necessary for future research.
5. Potential confounding factors were not controlled for, including students' prior achievement, teacher quality, socioeconomic background, access to digital tools, motivation, and prior exposure to computational thinking activities; any of these factors could influence HOTS.
6. Formal testing of gender equity (measurement invariance/differential item functioning) for CTS and HOTS items was not conducted; therefore, gender-based comparisons should be interpreted with these limitations in mind (El-Hamamsy et al., 2025).

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CONCLUSION

This study found a statistically significant positive relationship between Computational Thinking Skills (CTS) and Higher-Order Thinking Skills (HOTS) among high school students majoring in biology in Jakarta. Both groups demonstrated low proficiency levels in CTS (28.3%) and HOTS (42.2%). CTS accounted for 39.1% of the variance in HOTS among male students ($R = 0.626$) and 50.3% among female students ($R = 0.709$); however, a direct moderation test showed that the CTS–HOTS slope did not differ significantly by gender (interaction $p = 0.480$; $\Delta R^2 = 0.004$). H1 was supported, and H2 was not: the CTS–HOTS relationship does not appear to be influenced by gender in this sample.

The four CT practices, abstraction, algorithm design, decomposition, and evaluation, can therefore serve as valuable pedagogical focuses in biology instruction for both male and female students, and intervention and longitudinal studies are needed to test whether strengthening CTS leads to measurable improvements in HOTS. Cross-cultural replication with larger samples involving multiple schools, along with attention to instrument reliability and gender-fair measurement, will strengthen the evidence base for curriculum reform in STEM education.

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Ethical statement

This study was conducted in accordance with applicable research ethics principles. Ethical approval and official research permission were obtained from the Graduate School of Muhammadiyah University Prof. DR. HAMKA through an official request/approval letter No. 102/C.01.08/2023, dated January 25, 2023. The study was conducted at State Senior High School 65 Jakarta on February 2, 2023. All participants and the school provided informed consent prior to data collection, and participation was entirely voluntary. Participant confidentiality and anonymity were strictly maintained throughout the study in accordance with applicable personal data protection regulations and academic ethical standards.

Competing interests

The authors declare that there are no competing interests or conflicts of interest regarding the publication of this manuscript.

Author contributions

B.A; conceptualized the study and research design, supervised the research process, and reviewed and revised the manuscript., Y.C; collected the data, performed the investigation, and prepared the initial manuscript draft., L.S; conducted the data analysis, interpreted the findings, and contributed to manuscript editing., I; validated the research methodology, critically reviewed the manuscript, and provided academic supervision. All authors read and approved the final version of the manuscript.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AI disclosure

The authors declare that all content in this manuscript was prepared manually without the use of artificial intelligence (AI) for writing, content generation, structural organization, or idea development. The authors take full responsibility for the originality and integrity of the manuscript.

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