TYPE Original Research
PUBLISHED 19 September 2025
DOI 10.3389/feduc.2025.1625105

OPEN ACCESS

EDITED BY
Subramaniam Ramanathan,
Independent Scholar, Singapore, Singapore

REVIEWED BY
Jodi Asbell-Clarke,
TERC, United States
Silfia Ilma,
University of Borneo Tarakan, Indonesia

*CORRESPONDENCE
Wancen Ji
✉ wcji@hku.hk

RECEIVED 08 May 2025
ACCEPTED 05 September 2025
PUBLISHED 19 September 2025

CITATION
Ji W and Wong GKW (2025) Integrating problem-based learning and computational thinking: cultivating creative thinking in primary education.
Front. Educ. 10:1625105.
doi: 10.3389/feduc.2025.1625105

Integrating problem-based learning and computational thinking: cultivating creative thinking in primary education

Wancen Ji* and Gary K. W. Wong

Faculty of Education, The University of Hong Kong, Pokfulam, Hong Kong SAR, China

This study examines how integrating problem-based learning (PBL) with computational thinking (CT) contributes to cultivating creative thinking in senior primary school students (grades 5–6). Creativity is a critical skill for addressing complex, real-world problems, yet its development in education remains challenging. A four-week "Unmanned Supermarket" project was designed, incorporating CT skills such as problem decomposition, pattern recognition, and algorithm design. This study employed a creative thinking test tool based on Guilford's "Structure of Intellect" model and Torrance's "Creative Thinking Test," contextualized for the "Unmanned Supermarket" project to ensure content relevance. Data collection involved standardized paper-based tests conducted in a classroom environment, with pre-tests and post-tests administered 1 week before and after the intervention. Data analysis included descriptive statistics, normality tests, and the Wilcoxon signed-rank test, which is appropriate for small samples with non-normal distributions. Results showed significant improvements across all five dimensions of creative thinking and the total score ($p < 0.05$). The most substantial gains were observed in originality and elaboration ($Z = -3.547$, $p < 0.001$; $Z = -3.546$, $p < 0.001$). Importantly, all students demonstrated higher post-test total scores compared to pre-test scores, indicating consistent overall progress. These findings demonstrate how PBL, supported by CT, can enhance specific dimensions of creativity by encouraging innovative problem-solving and iterative design. This study provides insights into designing educational interventions that promote creativity through CT and PBL integration.

KEYWORDS

computational thinking, creative thinking, problem-based learning, different dimensions of creative thinking, primary education

1 Introduction

Cultivating creative thinking has become a critical goal in modern education, particularly in preparing students to address the increasingly complex challenges of the 21st century. Educational research highlights that fostering creative thinking not only enhances cognitive development but also equips students with future-ready skills, such as adaptability, collaboration, and interdisciplinary problem-solving (Torrance, n.d.). However, traditional subject-centered education often emphasizes rote memorization and standardized assessments, which may stifle creativity by limiting opportunities for open-ended exploration and authentic problem-solving (Beghetto and Kaufman, 2009).

In response to these challenges, project-based learning (PBL) has emerged as a student-centered teaching method that focuses on solving real-world problems and integrating knowledge across disciplines. PBL fosters creative thinking by immersing students in hands-on, authentic tasks that encourage exploration, experimentation, and continuous improvement. Studies indicate that PBL enhances creativity by offering opportunities for brainstorming, prototyping, and refining ideas—key steps in developing and applying innovative solutions (Capraro et al., 2013; Mishra and Henriksen, 2018). Additionally, PBL boosts intrinsic motivation by presenting students with open-ended, meaningful challenges, which increases their engagement and adaptability (Blumenfeld et al., 1991).

In recent years, CT has emerged as a robust framework for fostering innovative thinking within PBL. CT refers to the ability to solve problems systematically through decomposition, pattern recognition, abstraction, and algorithmic design (Wing, 2006; Grover and Pea, 2018). Teachers can integrate CT into PBL to equip students with structured tools and methods for tackling complex problems while nurturing creativity. Students are encouraged to explore novel solutions and refine their ideas iteratively in creative domains, such as designing algorithms and debugging systems (Pei et al., 2018). Like CT, PBL promotes interdisciplinary learning by connecting STEM-related concepts, allowing students to approach problems from diverse perspectives and develop innovative solutions (Angeli et al., 2016).

1.1 Research background

Despite the potential of CT and PBL to foster creative learning, their implementation in primary education remains unclear. There is a notable gap in understanding how younger students can apply these skills in classroom settings (Liu et al., 2024; Kong and Abelson, 2019). Most research has focused on non-traditional contexts like secondary education. While CT has been proven to enhance problem-solving and development (Grover and Pea, 2018), there is limited empirical evidence on its role in nurturing innovative thinking among primary school students. This gap highlights the need for studies exploring how CT-supported PBL can cultivate creativity in younger learners, especially in real-world, interdisciplinary contexts.

To address this gap, this pilot study employs a PBL approach centered on an “unmanned supermarket” project as an instructional framework to develop CT and creative thinking among senior primary school students. The “unmanned supermarket” project integrates multiple disciplines, including artificial intelligence, engineering, science, and architecture (Brennan and Resnick, 2012). By illustrating how CT can be effectively embedded into STEM-focused PBL activities, the project serves as a model for designing innovative teaching practices aligned with the Education Informatization and Education Modernization goals set by the Ministry of Education. Furthermore, integrating CT into K12 education reflects a growing trend in global education (UNESCO, 2019; CPC Central Committee and State Council, 2019).

Due to its rapid growth, unmanned retail technology serves as a compelling example for integrating CT and PBL into STEM education. From Amazon Go, launched by Amazon in 2018, to JD.com’s Seven Fresh unmanned supermarkets, these innovations have become a significant trend in the retail industry (Inman and Nikolova, 2017). Modern unmanned supermarkets utilize advanced technologies such as computer vision, contactless payment systems, the Internet of Things, and artificial intelligence (Szymanski et al., 2021). These systems provide valuable opportunities for creating STEM-focused PBL activities, enabling students to engage with real-world applications while building CT skills in structured environments.

Creativity is a core educational goal in the 21st century, and its five primary dimensions—fluency, flexibility, originality, elaboration, and redefinition—are closely tied to the “unmanned supermarket” project. This project leverages creativity by engaging students in designing multi-module systems, such as product recognition and payment systems. Students are encouraged to generate a variety of solutions (fluency) and propose optimal approaches for different scenarios (flexibility). Additionally, creating innovative features, such as personalized recommendations or new payment methods, fosters originality. Refining system designs and functional layouts (e.g., application interfaces and interaction processes) enhances elaboration, while redefining concepts like “unmanned cashier” or “smart retail” trains students to conceptualize innovative solutions. By integrating these dimensions of creativity with computational thinking, the “unmanned supermarket” project effectively bridges abstract concepts with practical tasks, providing a comprehensive framework for fostering creativity in real-world contexts.

1.2 Research significance

This study explores how integrating CT into a PBL framework fosters creative thinking among older primary school students. While CT is widely acknowledged for enhancing problem-solving and innovation through structured methods (Grover and Pea, 2018), its role in promoting creative thinking in primary education remains underexamined. This research offers new insights into how CT-supported PBL can enrich primary education by investigating the impact of the “unmanned supermarket” project on students’ creative thinking across dimensions such as fluency, flexibility, originality, elaboration, and redefinition.

Mishra et al. (2013) introduced the concept of creative computational thinking (CCT), emphasizing the intricate relationship between technology and creativity. Pei et al. (2018) builds on this foundation demonstrated that developing students’ creative problem-solving abilities, particularly in developing novel solutions to open-ended problems, is a skill that programming tasks, including CT skills, foster. The findings contribute to the growing research on joint and pupil- concentrated learning approaches and offer a model for integrating current teaching practices into appropriate curricula.

1.3 Research process and purposes

The primary objective of this study is to examine how CT-supported PBL influences students’ creative thinking abilities, particularly in the context of the “unmanned supermarket” project. Following the CT framework proposed by Grover and Pea (2013), this project integrates key components of CT, including decomposition, pattern recognition, abstraction, and algorithmic thinking. Throughout the project must be broken down into multiple subtasks. The supermarket system must also be broken down into distinct functional modules, such as product management, face recognition, product entry, and face payment. These activities allow students to break down complex and difficult-to-understand problems into small problems that are easy to solve. Students need to extract key issues and features from specific things, identify common patterns, and present the complex unmanned supermarket system in the form of a system model. These activities engage students in iterative design thinking processes, students cultivated creative thinking while developing practical problem-solving skills.

To evaluate the impact of this intervention, pre- and post- tests of creative thinking were conducted using adapted analysis tools designed for primary school students. These tools measured changes in creativity across five dimensions: fluency, flexibility, originality, elaboration, and redefinition. To coincide with this goal, existing creative thinking assessment tools were adapted to encompass project-related content for fifth- and sixth-grade students. These resources provide factual data on the effects of CT-supported PBL activities on creative thinking, offering a means to evaluate changes in each dimension of creativity. The results of the study are intended to contribute to a deeper understanding of how PBL, supported by computer-assisted instruction, fosters creativity in elementary education.

2 Theoretical framework

This study is grounded in the importance of creative thinking, emphasizing it as the ultimate goal of the learning process. Creative thinking is a vital skill for the 21st century, enabling individuals to create innovative thoughts, adapt to new challenges, and fix problems novelly. To effectively foster creative thinking, this study integrates constructivist theory, PBL, and CT into an interrelated framework. The design and implementation of a PBL program, the "Unmanned Supermarket" project for upper elementary students, was guided by this framework. This chapter first discusses the importance of creative thinking, explores the theoretical underpinnings of constructivism, and then examines how PBL and CT can be used as tools for fostering creativity.

2.1 Creative thinking

Creative thinking refers to the ability to generate new, valuable and innovative ideas by going beyond traditional thinking frameworks and developing solutions that are both innovative and practical (Runco and Acar, 2012; Sawyer, 2018). In the context of education, creativity is not solely an innate trait but a cognitive skill that can be cultivated through appropriate educational interventions (Cropley, 2015). Creative thinking is often conceptualized as a multidimensional construct. Building on Guilford's (1967) and Torrance's (1966) foundational work, contemporary researchers have refined creativity as consisting of several key dimensions:

1. Fluency: The ability to produce a large number of ideas or solutions in response to a prompt. Fluency reflects the breadth of a learner's ability to think creatively (Mishra and Henriksen, 2013).
2. Flexibility: The capacity to approach problems from diverse perspectives and adapt thinking strategies to new contexts (Beghetto and Kaufman, 2014).
3. Originality: The ability to generate unique and unconventional ideas that stand apart from typical solutions (Runco and Acar, 2012).
4. Elaboration: The skill to refine, expand, and detail ideas, making them more comprehensive and actionable (Cropley, 2020).
5. Redefinition: The ability to reinterpret existing concepts, objects, or problems in novel ways, often challenging traditional assumptions (Amabile and Pratt, 2016).

Creative thinking has significant implications for STEM education. By integrating PBL and CT, this study provides students with opportunities to solve real-world problems, encouraging them to think critically and creatively. Craft (2011) emphasized the importance of cultivating students' creative thinking in real life and learning. Research suggests that creative thinking is not exclusively inherent to gifted individuals but rather a cognitive capability that can be developed through systematic instruction and everyday learning experiences. This perspective has significantly influenced educational practices and pedagogical approaches to creativity development. By making creative thinking the core focus, this study sets the stage for understanding how constructivist principles, PBL, and CT are integrated to foster innovation and adaptability.

2.2 Constructivism

Constructivist learning theory provides the foundation for this study, emphasizing that learning is an active, dynamic, and social process in which learners construct their knowledge by connecting new information to their prior experiences (Ausubel, 1968). Constructivism supports the development of creative thinking by encouraging students to engage in inquiry, collaboration, and problem-solving within meaningful contexts.

Within the constructivist paradigm, problem-based learning (PBL) plays a central role in promoting active knowledge construction. PBL provides authentic, real-world scenarios where students collaboratively construct knowledge, fostering deeper engagement and critical thinking.

In this study, constructivism underpins the integration of PBL, CT, and creative thinking by emphasizing active participation, iterative problem-solving, and the transfer of knowledge to real-world contexts. This theoretical foundation ensures that students actively participate in constructing knowledge and applying it creatively. Specifically, the "unmanned supermarket" project exemplifies how constructivist principles are applied in practice:

> Student-Centered Learning: Students actively participate in designing and implementing solutions, taking ownership of their learning process.
>
> Knowledge Construction: Through iterative problem-solving and reflection, students construct new knowledge by connecting CT concepts (e.g., decomposition, pattern recognition) to real-world challenges.
>
> Collaborative Inquiry: Group-based activities foster collaboration and the exchange of diverse ideas, enabling students to approach problems from multiple perspectives.

Constructivism also supports the development of creativity by emphasizing exploration, experimentation, and iterative improvement.

For example, in the "unmanned supermarket" project, students engage in tasks such as designing flowcharts, debugging algorithms, and refining prototypes. These activities align with the key dimensions of creativity, particularly originality and elaboration, by encouraging students to generate unique ideas and develop them into actionable solutions.

This theoretical foundation ensures that students actively participate in constructing knowledge and applying it creatively.

2.3 PBL

PBL emphasizes student-centeredness, allowing students to construct in-depth knowledge through real and complex projects (Krajcik and Blumenfeld, 2006). The theoretical basis of PBL comes from constructivist learning theory, situational learning theory, PBL theory, etc. PBL emphasizes taking real problems as the basis, integrating knowledge and skills from multiple disciplines, and promoting students' comprehensive thinking ability and skills. Under the direction of teachers, students actively learn to construct knowledge and complete projects in a group.

The integration of PBL and computational thinking creates a collaborative learning environment that is particularly effective for problem solving using CT skills (Bell, 2010; Grover and Pea, 2013). In this study, PBL is used to create a synergistic learning environment where students develop both CT and creative thinking skills. For example, in the "unmanned supermarket" project, students naturally employ fundamental CT skills, including decomposition, pattern recognition (identifying repetitive elements in retail operations) and algorithmic thinking (designing step-by-step solutions for automated processes) (Blumenfeld et al., 1991; Bers, 2020).

By providing structured yet flexible opportunities for exploration, PBL encourages students to think holistically, collaborate effectively, and approach problems from multiple perspectives. This iterative process mirrors the dynamic nature of creative thinking, where students refine their ideas and develop innovative solutions through experimentation and feedback.

2.4 Computational thinking

CT serves as a cognitive tool within PBL activities, providing students with structured frameworks for solving complex problems. It is a fundamental skill for the 21st century, enabling problem-solving and fostering technological literacy across various disciplines (Wing, 2006; Kafai and Proctor, 2021).

The Angeli et al. framework outlines five core components of CT-decomposition, abstraction, pattern recognition, algorithm design, and debugging-and serves as the foundational structure for defining CT processes in this study. Angeli et al.'s framework provides a clear process and steps (in no order) for problem solving. The integration of the framework ensures a more comprehensive understanding of CT. It guide the design of CT-based PBL activities in this study, fostering both the systematic and creative dimensions of computational problem-solving.

The CT framework by Angeli et al. (2016) outlines five core components:

1. Decomposition: Breaking down complex systems into smaller, manageable parts. In the "unmanned supermarket" project, students decompose the system into subsystems. This approach reduces cognitive load and facilitates focused problem-solving.
2. Abstraction: Extracting relevant details and ignoring extraneous information. For example, students identify the essential attributes of a product (e.g., name, price, ID) and design a simplified data model to represent these features in the system.
3. Pattern Recognition: Identifying similarities and recurring patterns. Students analyze customer shopping behaviors and product use patterns to optimize the system design.
4. Algorithm Design: Creating step-by-step solutions. In this project, students develop algorithms for facial recognition, automatic checkout, and product categorization.
5. Debugging: Iteratively testing and refining solutions.

These elements are not independent; they form an iterative and interconnected process.

This study explores how CT can facilitate creative problem-solving, adaptability, and innovation, equipping students with the necessary skills to address complex, interdisciplinary challenges.

2.5 The connection between CT and creative thinking

CT and creative thinking are both indispensable skills for addressing the complex problems of the 21st century. CT provides a structured and analytical approach to problem-solving, while creative thinking introduces flexibility, innovation, and originality into the process. To explore their relationship, this section synthesizes insights from the theoretical frameworks of CT and creative thinking as presented earlier, aligning them with PBL principles to establish a cohesive understanding of how these dimensions interact.

2.5.1 Synergistic connection between CT and creative thinking

The relationship between CT and creative thinking can be understood through their interplay across four key aspects: problem-solving, abstract generalization, thought transfer, and evaluation and reflection. This synergy highlights how CT provides a framework for systematic thinking, while creative thinking expands the range of possibilities, enabling novel and effective solutions. Below is a detailed exploration of these aspects:

1. Problem-solving: In terms of problem-solving abilities, CT provides a structured analytical method for breaking down difficult problems into small, step-by-step, easy-to-solve problems, while creative thinking not only increases the ability to identify novel angles and methods for new problems but also improves people's ability to find unconventional solutions (DeHaan, 2009). The integration of these methods can lead to a more comprehensive understanding of problems and the development of solutions (Brennan and Resnick, 2012).
2. Abstract generalization: CT emphasizes abstraction by extracting relevant patterns and defining generalizable models (Grover and Pea, 2013). Creative thinking enriches this process by identifying unexpected relationships, enabling deeper

conceptual understanding and interdisciplinary connections (Shute et al., 2017).

3. Thought transfer: Knowledge and experience are transferred in both CT and creative thinking. CT ensures efficient application of knowledge through structured frameworks. Creative thinking introduces flexibility, enabling students to adapt and innovate across domains (Anwar and Aness, 2012). This integration promotes more effective learning transfer and enhances adaptability in different contexts (Sternberg and Lubart, 1999), as demonstrated in PBL activities.
4. Evaluation and reflection: The evaluation and reflection process is the intersection of CT and creative thinking. CT provides a systematic evaluation framework, and creative thinking provides a new evaluation perspective (Abraham, 2016). This combination allows for a more comprehensive evaluation and effective solution refinement (Shute et al., 2017). The combination of systematic reflection from CT and a deep reflective analysis from creative thinking can further enhance the overall learning experience (Siswono, 2011).

2.5.2 Integration of CT and creative thinking through the five dimensions of creativity

The five-dimensional framework of creative thinking—fluency, flexibility, originality, elaboration, and redefinition—provides a useful lens for understanding how CT contributes to the development of creativity. These dimensions are widely recognized in creativity research (see Chapter 2.4). By systematically linking the processes and practices of CT to these dimensions, it becomes evident that CT and creative thinking are mutually reinforcing, creating a powerful foundation for fostering innovation.

1. Fluency involves generating a large number of ideas or solutions (Milgram and Milgram, 1976). CT supports fluency by offering systematic tools (e.g., decomposition and pattern recognition) to generate and evaluate diverse solutions effectively.
2. Flexibility refers to the ability to approach problems from multiple perspectives and adapt to new contexts (Hidayat and Prabawanto, 2018). CT complements this by providing structured frameworks (e.g., abstraction techniques) that enable students to apply flexible thinking across different contexts and disciplines.
3. Originality represents the ability to generate new and unique ideas (Siswono, 2011; Ramalingam, 2020). CT's logical structures and algorithmic processes provide students with the technical means to implement new ideas, while creative thinking inspires them to break traditional boundaries and propose unique, innovative solutions.
4. Elaboration involves refining and enriching ideas to make them more comprehensive and actionable (Lombard and Grosser, 2008). The iterative optimization process inherent in CT (e.g., debugging and refining algorithms) aligns with creative thinking's emphasis on enriching and refining ideas, enabling students to produce more complete and effective solutions.
5. Redefinition involves challenging conventional assumptions and discovering new perspectives (Shadish et al., 2002). CT helps students analyze the essence of problems through systematic frameworks, while creative thinking encourages them to challenge conventional assumptions and discover new relationships, leading to groundbreaking solutions.

Each dimension of creative thinking is closely linked to specific elements of CT, demonstrating how CT cultivates creative thinking in educational settings. CT provides a structured and logical approach to problem-solving, while creative thinking introduces flexibility and innovation into the process. This theory provides inspiration and direction for the design of the "unmanned supermarket" project in this study and for how to cultivate students' CT ability through PBL.

2.6 Designing CT projects for upper primary school students

This pilot study presents the "unmanned supermarket" project as a practical application of the integrated theoretical framework of PBL, CT, and creative thinking. Designed for fifth- and sixth-grade primary school students, the project simulates a real-world unmanned retail environment, enabling students to apply CT skills collaboratively to design and develop a simplified unmanned supermarket system.

The central goal is to enable students to learn to use CT to solve problems while cultivating creativity through hands-on learning across disciplines. The project design is grounded in the theoretical constructs outlined in the preceding sections, ensuring alignment with the educational research desideratum. It transitions from foundational theoretical concepts to practical application, emphasizing a progression from concrete tasks to abstract modeling and from process design to algorithm implementation. Activities throughout each stage of the program are carried out by learning to apply CT skills to problem solving and cultivating creative thinking, while filling key gaps in theoretical research and providing guidance for the formation of specific research questions.

To introduce CT concepts in a simple and accessible way, the project begins with a familiar and tangible context: cookie-making. This initial activity provides a foundation for understanding key CT principles, which are later applied in the more complex "unmanned supermarket" project. The progression from cookie-making to the unmanned supermarket reflects a deliberate transition from simple, concrete tasks to more abstract, interdisciplinary challenges.

1. Familiar Context to Reduce Cognitive Load: Cookie-making are familiar, everyday tasks that reduce the cognitive burden of learning CT concepts.
2. Students watched a video demonstrating cookie-making, then decomposed the processes into smaller subtasks (e.g., preparing ingredients, assembling, baking). They abstracted a generalized model applicable to various tasks: Define task goals, prepare necessary resources and complete subtasks step by step. Students described the processes of making cookies using simple algorithmic steps based on their flowcharts (e.g., input, steps, output).

The transition to the "unmanned supermarket" project builds on the foundational CT skills introduced in the cookie-making scenario. This project provides a complex, real-world problem-solving context that encourages students to collaboratively design and implement a working system. The project is divided into five main stages, each designed to develop specific CT skills and cultivate creativity.

1. Real-World Context and Problem Exploration: Students are introduced to the concept of unmanned supermarkets through videos and discussions. They analyze the technologies used in such systems, the challenges these systems face, and the potential solutions.
2. Problem Decomposition and System Simulation: Students use CT to decompose the unmanned supermarket system into major components (e.g., commodity recognition, face recognition, payment systems). They simulate shopping scenarios in the supermarket to verify the effectiveness of their decomposition process.
3. Designing Flowcharts and Identifying Key Information: Students work collaboratively to design flowcharts and distribution diagrams, outlining a simplified shopping process for an unmanned supermarket. They are encouraged to use CT to identify core content and filter out non-essential information.
4. Coding and System Integration: Using scaffolding teaching methods, students are provided with basic code templates to help them gradually complete the coding for each subsystem, including product recognition, face recognition, price accumulation, and payment. These subsystems are then integrated into a complete coding system.
5. Testing, Feedback, and debugging: Students test their projects in simulated real-world scenarios to ensure functionality. Each group presents their work, receives peer feedback, and identifies areas for improvement. They then refine their systems, implementing creative solutions to address any issues.

The design of the "unmanned supermarket" project directly reflects the theoretical foundation of PBL, CT, and creative thinking, addressing critical research gaps identified in previous sections. The design of the "unmanned supermarket" project directly reflects the theoretical foundation of PBL, CT, and creative thinking, addressing critical research gaps identified in previous sections. The project demonstrates how CT serves as a tool within the PBL framework to cultivate creative thinking across its five dimensions, while also enabling students to systematically solve real-world problems.

This study explores the interaction of PBL, CT, and creative thinking through the "unmanned supermarket" project, formulating the following research questions:

> RQ1: How does the unmanned supermarket project effectively cultivate students' CT ability?

This question examines the role of the project in fostering specific CT skills, such as decomposition, abstraction, and algorithmic design, among upper primary school students.

> RQ2: How can a tool suitable for evaluating the creative thinking ability of senior primary school students be developed?

This question addresses the need for a reliable and valid assessment framework for measuring creativity in the context of CT-integrated activities.

> RQ3: How do computational thinking skills integrated into problem-based learning activities in the unmanned supermarket project indirectly support different dimensions of creative thinking?

This question explores the interplay between CT and creative thinking, focusing on how CT skills (e.g., problem decomposition, abstraction) enhance creativity across its five dimensions (fluency, flexibility, originality, elaboration, redefinition).

3 Research methods

3.1 Research design

This study adopts a pre-test and post-test design in a quasi-experimental design, which allows us to compare the changes in participants' creative thinking test scores before and after receiving the "unmanned supermarket" project intervention (Cook and Campbell, 1979). The intervention was designed based on the pedagogical principles of problem-based learning (PBL), emphasizing real-world problem-solving, collaborative learning, and interdisciplinary integration to support the development of creative thinking among upper primary school students.

Implementation Context and Decision Basis: Shenzhen, where this study is conducted, is one of the key pilot cities for China's education modernization and the Education Informatization 2.0 Action Plan. In China, CT and programming education are gradually being promoted in basic education, particularly in the upper grades of primary school (Grades 5–6). Relevant programming courses and technological applications, such as artificial intelligence, have increasingly been integrated into classrooms. The selected school for this study is a public bilingual primary school that, in addition to teaching core courses prescribed by the national curriculum standards, offers additional course modules, including programming and project-based learning. These characteristics provide suitable experimental conditions for the research. Participants already have a certain foundation in programming and project-based learning, enabling them to comprehend and engage with the "Unmanned Supermarket" project.

The design of the "Unmanned Supermarket" project was guided by PBL principles, with tasks structured to engage students in problem decomposition, collaborative brainstorming, iterative prototyping, and peer evaluation. Computational thinking (CT) elements, such as problem decomposition and abstraction, were embedded within the PBL framework as cognitive tools to support students' engagement with complex tasks. Due to time and resource constraints, this study does not directly measure CT abilities, as the research focus is on evaluating how PBL activities, incorporating CT elements, can collectively enhance creative thinking. While a control group could provide a more robust comparative analysis, the exclusion of a control group was a deliberate methodological choice due to the following considerations:

1. Constraints of the School's Teaching Environment: During the implementation of the study, randomly assigning students into experimental and control groups could have disrupted the school's regular teaching schedule. The school involved in this

study provided only one class for the research, with a limited number of students (Pei et al., 2018), making it impractical to establish both experimental and control groups. Additionally, school administrators and teachers preferred a unified teaching approach for the entire class to avoid potential dissatisfaction from students or parents. As Shadish et al. (2002) suggest, single-group pretest-posttest designs are a valid alternative in situations where randomization or control groups are impractical.
2. Limitations in Resources and Time: The study was conducted over a 4-week period, during which the teaching design and implementation were completed. Designing a control group would have required additional teaching resources and more time for coordination, which were not feasible within the constraints of this study. To minimize disruption to the school's teaching schedule and ensure the study's feasibility, a single-group pretest-posttest design was chosen.
3. Ethical Considerations: Establishing a control group would have meant that some students would not have access to the innovative teaching offered by the "Unmanned Supermarket" project. This could have raised concerns about fairness, particularly given the expectations of the school and parents. Cohen et al. (2018) emphasize that educational research must prioritize fairness and equitable access to opportunities, particularly in interventions designed to improve critical skills like computational and creative thinking. To avoid ethical issues, all students were included in the teaching intervention.

While the lack of a control group may limit the generalizability of the findings, this study addresses this limitation through robust statistical analyses, including paired-sample *t*-tests and effect size calculations, to assess the magnitude of changes in creative thinking. As Gliner et al. (2016) suggest, these methods enhance the reliability and validity of single-group designs.

In the school education environment, randomly assigning students to experimental and control groups will disrupt the normal learning life of the school and is impractical. However, the pre- and post-test design can be used in the existing class structure (Cook and Campbell, 1979), thus minimizing the impact on normal school life and making it easier to obtain the support of school administrators and teachers. This design method allows for a direct comparison of the creative thinking performance of the same group of students before and after the "unmanned supermarket" project intervention and for the influence of individual differences to be controlled (Dimitrov and Rumrill, 2003).

Experimental research without a control group may affect the internal validity of the study because it is impossible to rule out the influence of other student factors on the results (Shadish, 2002). When intervention and testing are carried out in the same group, it is easy for the pre-test to affect the results of the post-test. This is because students may predict or be more adaptable to the questions in the post-test through the questions in the pre-test.

The instructional intervention spans 4 weeks, comprising six 90 min sessions, with sufficient temporal spacing to minimize testing effects between the pre- and post-assessments.

In terms of the implementation of this intervention, one of the authors was actually the course instructor leading the classroom teaching in this study, who was a graduate student at that time studying in the field of educational technology. Another author who was the project supervisor had helped with the review of the research design and the intervention design to ensure that the designs were able to fulfil the research objectives. This arrangement also helped minimize the issues if an instructor was recruited outside of the project who may not have a complete understanding of our expectation, thus releasing our workload in training the instructor to teach according to our design.

3.2 Study subjects

The subjects of this research are 17 fifth- and sixth-grade students from a public bilingual primary school in Shenzhen (all males), aged between 10 and 12 years old. According to Piaget's (1972) cognitive development theory, students of this age group are in the transition period from the concrete operational stage to the formal operational stage and have certain logical thinking and abstract reasoning abilities. The senior primary school students at this school have already acquired basic programming and project learning abilities; thus, they can effectively understand and participate in the "unmanned supermarket" project. Senior primary school is a critical period for cultivating students' creative thinking (Torrance, 1968; Runco, 2014).

The selection of senior primary school students (grades 5–6) as research subjects was guided by the following considerations:

1. From the perspective of cognitive development stage, Piaget (2001) cognitive development theory points out that children aged 11–12 are in the critical period of transition from concrete operations to formal operations (Feldman, 2003). Students of this age group have already acquired basic logical thinking ability and are able to perform abstract thinking and hypothetical deductive reasoning, which provides an important cognitive basis for learning computational thinking (Diamond, 2013).
2. From the perspective of learning ability, Studies have documented that fifth- and sixth-grade typically possess foundational mathematical competencies and problem-solving strategies that prepare them for introductory programming concepts (Rich et al., 2017). Their natural curiosity and intrinsic motivation for learning, combined with heightened creative potential, create optimal conditions for developing both computational and creative thinking skills (Clements and Sarama, 2020).
3. From the perspective of curriculum setting, the upper grade of primary school is an important stage for carrying out STEM education (English, 2016). The unmanned supermarket project exemplifies how multidisciplinary knowledge can be synthesized to foster comprehensive application abilities (Kelley and Knowles, 2016), directly corresponding to the computational thinking framework established by Grover and Pea (2013).
4. From the perspective of educational practice needs, current research on the impact of computational thinking on creative thinking is mostly concentrated in the middle school stage (Kong and Abelson, 2019), while empirical research on the primary school stage, especially the senior grades, remains limited. Selecting this age group for research can provide

important theoretical and practical references for the development of computational thinking education in the primary school stage.
5. From the perspective of developmental psychology, fifth and sixth grade students are in the critical period of creative development. As Torrance (1988) pointed out, 9–12 years old is an important period for the development of creativity. Timely and targeted intervention can help stimulate students' creative potential and lay a good foundation for the cultivation of future innovative talents.

All students had prior experience with basic programming courses (e.g., initial use of Scratch or Mind+), demonstrating certain abilities in logical reasoning and abstract thinking, as well as an understanding and application of core computational thinking concepts. The students' families placed a high value on education, and some students had received extracurricular training in programming and artificial intelligence, which may have given them an advantage in participating in the "Unmanned Supermarket" project. Additionally, students also demonstrated strong collaboration skills and team awareness in their daily studies, which laid a solid foundation for the successful implementation of PBL.

The research subjects were selected via convenient sampling; that is, students from a class in the school were selected. However, this sampling method may have a certain influence on the generalization and availability of the research results (Etikan et al., 2016). Considering the need to obtain consent from school administrators, teachers, the guardians of participating students, and the students themselves and considering the research resources and feasibility, this selection method is the most reasonable choice.

3.3 Specific goals and role of the "cookie-making" stage

In the "Cookie-making" stage, students engaged in a familiar and simple task to reduce cognitive load while laying the foundation for the subsequent, more complex "Unmanned Supermarket" project. The objectives of this stage are as follows:

3.3.1 Reducing cognitive load

The cookie-making activity, a task familiar in students' daily lives, was selected as the starting point to minimize cognitive barriers associated with learning new concepts. This familiar context helped students focus on the core skills of computational thinking (CT), such as decomposition and abstraction, without being overwhelmed by an unfamiliar task.

3.3.2 Introducing core computational thinking concepts

During the "Cookie-making" stage, students were introduced to key CT concepts through observation and task breakdown:

1. Decomposition: Students divided the cookie-making process into smaller, manageable subtasks.
2. Abstraction: Students extracted critical information from the task and generalized it into a task model.

3.3.3 Providing a transition to the "unmanned supermarket" project

This stage served as a bridge, equipping students with the skills and mindset necessary for the more complex "Unmanned Supermarket" project:

1. Transition from Simple to Complex Tasks: By learning to break down the cookie-making process into smaller steps, students acquired problem decomposition skills that were directly applied to decomposing the "Unmanned Supermarket" system into functional modules (e.g., product recognition, payment systems).
2. Transition from Concrete to Abstract Thinking: The abstraction skills practiced during cookie-making (e.g., designing flowcharts for cookie-making steps) provided a foundation for creating flowcharts for the supermarket's system processes.
3. Hands-On Practice and Collaboration: Working in groups to decompose the cookie-making task fostered collaboration and hands-on problem-solving skills, preparing students for teamwork during the supermarket project.

3.4 "Unmanned supermarket" project introduction

This study draws on Maastricht seven jump (Schmidt, 1983) teaching method as the main teaching design framework, and combines it with Jonassen's structured problem-solving model for teaching design. The reason for choosing this model is that its systematic and structured characteristics are particularly suitable for cultivating computational thinking skills and solving problems with strong abstract thinking such as programming. And it can stimulate students to solve real-world problems, work collaboratively, activate higher cognitive levels, and organize their own learning process (Woltering et al., 2009). Together, these approaches provided a robust pedagogical foundation for cultivating creative thinking among students through PBL.

The Maastricht Seven Jump Teaching Method is a systematic process designed to solve complex problems through group collaboration and inquiry. It consists of seven structured steps (Schmidt, 1983). The first step, clarifying terms and concepts, ensures that all participants have a shared understanding of the topic. This is followed by problem definition, where the core issues to be addressed are identified. In the third step, problem analysis (brainstorming), potential solutions are generated through group discussion. The fourth step, systematic inventory, involves organizing and prioritizing these solutions to create a coherent approach. Next, learning objectives are established by identifying knowledge gaps and setting specific goals to address them. The sixth step, self-directed learning, encourages participants to independently study and gather the necessary information to close these gaps. Finally, the process concludes with synthesis, where findings are presented, peer evaluations are conducted, and solutions are refined. This method fosters active learning, collaboration, critical thinking, and problem-solving, making it a highly effective tool for complex educational scenarios. For instance, during the payment system design phase, one group created a process based on facial recognition technology. They decomposed the system into three main modules: facial recognition, price accumulation, and automated payment, and implemented these using HUSKYLENS and Mind+ tools. Additionally, the group introduced an "individualized recommendation" feature, where the system suggests products based on customer shopping history. This design not only demonstrates their use of computational thinking skills (e.g., decomposition and pattern recognition) but also highlights their improvements in originality and elaboration.

Table 1 outlines how the Seven Jump framework was applied to the "Unmanned Supermarket" project:

The "unmanned supermarket" project provides a unique and authentic learning environment that fosters creativity by integrating real-world challenges with CT and PBL. Unmanned supermarkets represent a complex, real-world problem space that incorporates advanced technologies such as artificial intelligence, computer vision, and the Internet of Things. This complexity offers students an interdisciplinary context in which they are tasked with designing innovative solutions to challenges like improving customer experiences, optimizing inventory management systems, and addressing technical or security issues.

By engaging with these practical problems, students are encouraged to think divergently and generate novel solutions, aligning with the key dimensions of creative thinking, including originality, flexibility, and elaboration. The project is intentionally designed as an open-ended challenge, requiring students to decompose the supermarket system into functional modules (e.g., product recognition, facial recognition for payments) and create solutions using computational tools. This open-ended nature encourages students to explore multiple perspectives, adapt their ideas, and elaborate on their solutions collaboratively. Moreover, the project integrates concepts from computer science, mathematics, and engineering, encouraging students to apply interdisciplinary knowledge to solve complex problems. The project also creates a safe space for experimentation, where students can test ideas and explore unconventional approaches without the fear of failure. This aligns with the goals of PBL by promoting active learning, creativity, and the ability to tackle real-world challenges. Tools like Mind+ and HUSKYLENS allow for rapid prototyping and immediate feedback, stimulating innovative thinking. Overall, the "unmanned supermarket" project demonstrates its suitability as a platform for fostering creativity in a dynamic, interdisciplinary, and real-world context.

This study, based on constructivist theory and combining the frameworks of PBL and CT, designed the "Unmanned Supermarket" project, aiming to cultivate creative thinking and problem-solving skills among upper primary school students through real-world learning contexts. Students work together in groups to use artificial intelligence technology (such as HUSKYLENS) and programming tools (such as Mind+) to simulate the operating system of an unmanned supermarket. By combining the specific supermarket scene with the abstract concept of CT, students can better transfer knowledge. The project combines programming tools and artificial intelligence technology to enable students to learn and apply advanced technologies. The pedagogical framework facilitates the development of STEM-related competencies while fostering student engagement in emerging technologies and CT paradigms.

3.4.1 A detailed description of the project implementation process

Week 1: The teaching process used the analogy of making cookies to introduce students to the five core elements of computational thinking (CT) as tools for problem-solving within the problem-based learning (PBL) framework. This analogy helped students understand how to decompose complex problems, recognize patterns, and develop solutions, while stimulating their creativity and problem-solving skills. Students began by watching

TABLE 1 Seven jump framework implementation.

Jump step	Activities	Timing
1 Clarifying terms and objects	• Introduce the concepts and terms related to unmanned supermarkets. • Clarify the core elements of computational thinking involved in the project. • Establish a common knowledge base.	Week 1
2 Problem definition	• Analyze specific problems in unmanned supermarket operations. • Determine the core issues that need to be solved. • Clearly define project goals and expected outcomes.	Week 1
3 Problem analysis (Brain storming)	• Use brainstorming to discuss possible solutions. • Apply decomposition strategies from computational thinking. • Draw problem analysis diagrams.	Week 2
4 Systematic inventory	• Categorize and organize problem solutions. • Establish solution priorities. • Formulate a preliminary project plan.	Week 3
5 Learning objectives	• Identify the knowledge points and skills that need to be mastered. • Set individual and group learning goals. • Develop a learning plan.	Week 3–4
6 Self-directed Learning	• Conduct independent leaning of programming skills. • Find relevant resources and reference materials. • Complete assigned tasks	Week 3–4
7 Synthesis	• Group presentation of leaning results. • Conduct peer evaluation and feedback. • Optimization and improvement scheme.	Week 4

a real-life video about unmanned supermarkets. In groups, they discussed the basic functions and operating principles of unmanned supermarkets. Students were then guided to list potential problems (e.g., technical failures, security risks) and brainstorm preliminary solutions. For example, one student suggested: "If product recognition fails, customers might be charged incorrectly."

Week 2: Students learned how to break down complex problems into smaller tasks. Working in groups, they divided the unmanned supermarket system into modules (e.g., product recognition, inventory management, payment system) and created flowcharts for each module. For instance, one group designed a "payment module" with the following steps: facial recognition → price calculation → automatic payment → feedback notification.

Week 3: Students started programming using the Mind+ tool. Teachers provided basic code templates (e.g., a framework for the product recognition algorithm), and students completed specific functional tasks based on the requirements. For example, in the "product recognition module," students used HUSKYLENS devices to train the system to recognize different products and programmed it to display prices.

Week 4: Each group integrated their independently developed modules into a complete unmanned supermarket system and conducted functional tests. Each group presented their design and received feedback from other groups. For example, one group proposed the idea of "using facial recognition to recommend personalized products" during their presentation, which received positive feedback from peers. Finally, students optimized their system designs based on the feedback and submitted their final versions.

By embedding CT elements (e.g., problem decomposition, abstraction) within PBL activities, students were able to approach complex problems systematically without CT being the primary focus of the intervention. In summary, the "unmanned supermarket" project used PBL principles to create an engaging, real-world learning environment that fostered creativity, collaboration, and interdisciplinary problem-solving.

3.5 Creative thinking test tools

The creative thinking test tool used in this study was designed based on Guilford's "Intelligence Structure Model" (1967) and Torrance's "Creative Thinking Test" (1988). Creative thinking is divided into five different dimensions: fluency, flexibility, originality, elaboration, and redefinition. These dimensions are closely aligned with the pedagogical goals of the PBL framework used in this study, ensuring that the test content is contextually relevant and reflective of the students' learning experiences.

The main reason for developing this measurement tool is the existing creativity measurement tools, such as the TTCT, are highly authoritative and widely applied, their content is relatively general and may not fully align with the specific context of this study (i.e., the "Unmanned Supermarket" project). Therefore, based on existing creativity assessment tools (e.g., TTCT), a contextually relevant measurement instrument tailored to the study's specific setting was designed. This ensured that the test content was closely aligned with students' learning background and the project's content, thereby enabling a more accurate evaluation of the intervention's effectiveness.

The measurement tool developed for this study incorporates the five dimensions of creative thinking (fluency, flexibility, originality, elaboration, and redefinition) and is contextualized within the "Unmanned Supermarket" project. Specific tasks were designed based on this context. This contextualized design not only enhances student engagement but also effectively mitigates the disconnect between the test content and the learning context.

Below are the design details and theoretical basis for each dimension:

1. Fluency:

A Test Design: Students were asked to generate as many ideas as possible in response to prompts related to the "Unmanned Supermarket" project, such as listing potential intelligent systems or safety hazards.

B Theoretical Basis: Derived from Torrance's "unrestricted response" test format, fluency measures the ability to produce a large quantity of ideas and is a key indicator of divergent thinking (Runco and Acar, 2012).

2. Flexibility:

A Test Design: Students were required to examine the "Unmanned Supermarket" from various perspectives and propose alternative solutions or optimizations for different scenarios.

B Theoretical Basis: This dimension reflects the ability to shift thinking and approach problems from diverse angles, rooted in Guilford's (1967)"flexibility of thinking" concept and modern creativity research emphasizing perspective changes.

3. Originality:

A Test Design: Students were tasked with proposing novel ideas, such as designing advanced payment systems or innovative marketing strategies for the supermarket.

B Theoretical Basis: Originality is measured by the uniqueness and unconventionality of ideas, consistent with Torrance's (1988) "uniqueness score" and Runco and Jaeger's (2012) emphasis on novelty in creativity assessment.

4. Elaboration:

A. Test Design: Students were asked to expand on existing ideas, adding details to layouts, processes, or system designs they had previously created.

B. Theoretical Basis: This dimension assesses the ability to refine and elaborate ideas, drawing from Urban and Jellen's "perfectionist" test theory and Cropley's (2020) conceptualization of elaborative thinking.

5. Redefinition:

A Test Design: Students were asked to redefine terms such as "unmanned cashier" or propose new names and concepts for intelligent systems.

B Theoretical Basis: Inspired by Torrance's (1966) "peculiarity test," redefinition measures conceptual creativity by challenging traditional definitions and exploring new meanings (Plucker and Renzulli, 1999).

To ensure the scientific rigor and applicability of the creativity measurement tool used in this study, one of the authors of this paper who is a professor in education with experiences in measurement tool design was invited to evaluate its content validity. His extensive research experience and significant academic influence in the fields of computational thinking, artificial intelligence education, and STEM education provide a solid foundation for the validity assessment of the tool... since he was also the supervisor of the research study, his role would only need to focus on the validity of the contents, instead of demonstrating potential bias. Certainly, this posts a limitation of the validation process when there was no other external reviewers reviewing the contents. Because of the nature of this being a pilot study, we agreed that further validation may be needed in the next phase of our study. We have already included this explanation to the limitation section of this paper.

Due to the constraints of time and resources, this study has not yet conducted small-scale experimental validation of the self-developed measurement tool. However, to ensure the scientific rigor and applicability of the tool, the following alternative approaches were adopted:

1. Dual Logical Validation: Theoretical and Contextual:

A The tool's design is strictly based on the five-dimensional theoretical framework of creativity (fluency, flexibility, originality, elaboration, and redefinition) and references the widely used TTCT question formats to ensure consistency with established measurement theories.

B The measurement tasks are directly aligned with the specific tasks and learning content of the "Unmanned Supermarket" project. For example, the task "Design an innovative function for an unmanned supermarket" is highly relevant to the core objectives of the project. This contextualized design enables the tool to better capture students' creative performance during computational thinking training.

2. Expert Validity Evaluation:

A After the development of the tool, its content validity was assessed through expert review. Based on the experts' suggestions, certain questions were revised. For instance, the task "Design an intelligent system for an unmanned supermarket" was refined to "Design an intelligent payment system for an unmanned supermarket, and describe its functions and operational steps" to increase specificity and ease of response.

B While the expert review provided valuable insights, the lack of additional external reviewers is acknowledged as a limitation. As this is a pilot study, further validation, including larger-scale testing, is planned for future research.

3. Indirect Validation of Results Data:

Although formal pilot testing or reliability and validity analysis was not conducted, the effectiveness of the tool was indirectly validated through pre- and post-intervention data. Analysis of the data revealed significant improvements in students' scores across all five dimensions of creativity, with trends consistent with theoretical expectations. For example, the dimensions of originality and elaboration showed the most significant improvements after the intervention, aligning with the hypothesis in creativity theory that "innovative activities can significantly stimulate students' originality (Craft, 2011)."

The complete test questions and scoring form are presented in the Appendix A, B.

3.6 Data collection and analysis methods

The study employed a quantitative approach to measure the impact of the intervention. This study did not directly measure CT abilities during data collection, primarily based on the following considerations: (1) The instructional design of the "Unmanned Supermarket" project has embedded the core elements of CT abilities, and their improvement can be inferred through the task completion process; (2) directly measuring CT abilities could increase students' cognitive load, potentially affecting the intervention's effectiveness; (3) relevant literature (e.g., Angeli et al., 2016) indicates that the enhancement of CT abilities is an expected outcome in programming- and project-based learning activities. Therefore, this study indirectly validated the potential impact of CT through changes in creative thinking.

The study was approved by the research ethics committee of authors' institution. All the participants including the school principal, teachers, parents and students gave the consent to participate in this project and agreed on the data collection and retention. Each dimension was scored on a scale of 0–10, with a total maximum score of 50 points. The scoring criteria for each dimension were developed according to established rubrics, ensuring consistency and reliability.

The pre- and post-test assessments were conducted in a standardized environment using a pen-and-paper format. This approach was chosen to ensure accessibility for all participants, as not all students had prior experience with computer-based testing, which could have introduced additional variability in the results. Both tests were administered in the same classroom under the supervision of a researcher and a teacher to ensure consistency and minimize distractions. Students were provided clear instructions before the test began, and the time limit was consistent across both assessments.

The pre-test was conducted 1 week prior to the "unmanned supermarket" project intervention, while the post-test took place 1 week after the intervention. The standardized environment ensured that no external factors influenced the testing conditions. Students were given ample time to complete the assessment, and any clarifications regarding task instructions were provided in real-time.

1. Pre-test: conducted 1 week before the "unmanned supermarket" project intervention.
2. Post-test: conducted 1 week after the intervention.

3.6.1 Data collection ethics

1. Informed consent was obtained from the school, parents, and students before data collection began.

2. It was ensured that all participants understood the intention and process of the study, as well as their right to withdraw at any time.
3. All data were stored securely and were only accessible to members of the research team.

3.6.2 Data analysis methods

To evaluate the impact of the "Unmanned Supermarket" project intervention on students' creative thinking, this study employed quantitative data analysis using IBM SPSS Statistics. The primary goal of the analysis was to assess changes in students' creative thinking across five dimensions: fluency, flexibility, originality, elaboration, and redefinition, as measured through pre- and post-test assessments.

1. Descriptive Statistics: Descriptive statistics were used to summarize the distribution of the data, including minimum and maximum values, mean scores, and standard deviations, providing an overview of students' pre- and post-test creative thinking performance. In addition, skewness and kurtosis values were calculated to evaluate the distributional characteristics of the data.
2. Normality Testing: Given the relatively small sample size ($N = 17$), the Shapiro–Wilk test was employed to examine whether the pre-test and post-test data met the assumption of normality. The results indicated that several variables (e.g., flexibility, originality, elaboration, and redefinition) significantly deviated from a normal distribution.
3. Wilcoxon Signed-Rank Test: Because the normality assumption was not met for multiple key variables, the Wilcoxon signed-rank test, a non-parametric alternative to the paired-sample t-test, was used to evaluate differences between pre-test and post-test scores. This test is appropriate for small samples and paired data that are not normally distributed. The Z-value and p-value were reported to determine statistical significance for each dimension of creative thinking.

4 Results

4.1 Descriptive statistics

Through a detailed descriptive statistical analysis, we obtained a comprehensive understanding of the basic characteristics of the research sample, the distribution of creative thinking scores, and the performance of the projects. This analysis provides a clear foundation for evaluating the relationships between the intervention activities and observed changes in creative thinking dimensions.

Table 2 presents the basic characteristics of the research sample. The study involved 17 fifth- and sixth-grade primary school students, all of whom had previous programming experience but no prior exposure to formal CT concepts. This ensured that any observed improvements in creative thinking could be primarily attributed to the intervention activities rather than pre-existing knowledge of CT.

In the payment module design, students applied computational thinking skills such as decomposition and pattern recognition, resulting in innovative features like multilingual support for the payment interface. This directly correlates with the observed 110.13% increase in originality scores and the 90.03% improvement in elaboration scores. Such results demonstrate the effectiveness of open-ended tasks in enhancing students' creative thinking.

The data presented in Table 3 reveal that the students' total scores in the creative thinking post-test increased overall, and both the lowest and highest scores improved compared with those in the pre-test. The average scores of the pre- and post-tests increased by about 8.82 points, which shows that the intervention of the "unmanned supermarket" CT project has a positive effect on improving students' creative thinking. All participants completed the pre- and post-tests, thus increasing the reliability of the results. Notably, both the minimum and maximum scores increased, indicating that the intervention benefited students across a wide range of initial creative thinking abilities. Additionally, the standard deviation increased slightly, reflecting a greater diversity in post-test performance. This diversity may indicate that the intervention allowed students to develop their creative thinking skills at different rates, potentially influenced by individual differences in engagement or baseline ability.

Key observations:

1. Overall Score Increase: The average increase of 8.82 points highlights the effectiveness of the CT intervention in enhancing creative thinking.
2. Standard Deviation Trends: The slight increase in standard deviation (from 6.789 to 7.203) suggests that while all students improved, the range of improvement varied. This could be attributed to differing levels of baseline skills, motivation, or engagement during the intervention.
3. Post-Test Reliability: The consistency in data collection (all participants completed both pre- and post-tests) strengthens the reliability of the findings.

4.2 Normality tests

Table 4 presents the descriptive statistics, skewness, kurtosis, and Shapiro–Wilk test results for each dimension of creative thinking and the total score.

The results confirmed that several variables significantly deviated from normality. Therefore, the Wilcoxon signed-rank test was employed in subsequent analyses.

TABLE 2 Description of basic characteristics of samples.

Characteristic	Numerical value or ratio
Sample size	17
Grade distribution	primary school fifth and sixth grades
Previously participated in programming courses	Yes (100%)
Have you ever understood the concept of computational thinking?	No (100%)

TABLE 3 Creative thinking score distribution.

	N	Minimum	Maximum	Average value	Standard deviation
Total pre-test	17	9	31	18.71	6.789
Total post-test	17	14	36	27.53	7.203
Number of valid cases	17				

4.3 Analysis of changes in different dimensions of creative thinking

Given the violation of normality assumptions, the Wilcoxon signed-rank test was conducted to compare students' pre-test and post-test scores across the five dimensions of creative thinking and the total score. The results revealed significant improvements across all five dimensions of creative thinking, as well as the total score. The most substantial gains were observed in Originality ($Z = -3.547$, $p < 0.001$) and Elaboration ($Z = -3.546$, $p < 0.001$). Importantly, for the total score, all participants showed post-test scores higher than pre-test scores (no negative ranks), indicating a systematic and consistent improvement in overall creativity. Although Fluency and Redefinition showed relatively smaller improvements, both dimensions still reached statistical significance (Table 5).

Fluency:

The average fluency score of the students increased from 6.88 in the pre-test to 7.71 in the post-test after participating in the "Unmanned Supermarket" project, reflecting an improvement of 0.82 points (an 11.98% increase). The Wilcoxon signed-rank test indicated that this difference was statistically significant ($Z = -2.435$, $p = 0.015$). However, the magnitude of improvement in fluency was notably smaller compared with the other dimensions of creative thinking. Several possible explanations can be considered:

1. Higher Initial Level, Limited Room for Improvement: As a fundamental dimension of creative thinking, fluency tests measure students' ability to generate a large number of ideas within a short time. Participants in the study had a pre-intervention fluency score that was already higher than other dimensions. This suggests that students were relatively strong in generating many ideas even before the intervention, leaving less room for improvement.
2. Weaker Targeting of Fluency in the Intervention Content: Although the "Unmanned Supermarket" project trained students' computational thinking through tasks such as task decomposition and pattern recognition, the intervention was primarily designed to cultivate students' creative thinking. As a result, students had relatively fewer opportunities to practice generating a large number of ideas, which may have led to the lower improvement in fluency scores.
3. Time Constraints of the Intervention: As a dimension of creative thinking that is relatively more challenging to significantly enhance, fluency may require a longer period of intervention to observe substantial changes. This study's intervention lasted 4 weeks (six sessions), which may still be insufficient for in-depth training to significantly improve fluency.

Flexibility:

The average flexibility score rose from 4.06 in the pre-test to 5.82 in the post-test, an increase of 1.76 points (43.35%). The Wilcoxon signed-rank test confirmed a significant improvement ($Z = -2.993$, $p = 0.003$). This growth suggests that students became more capable of approaching problems from multiple perspectives. Possible reasons include:

1. The project required students to address supermarket-related problems from various functional perspectives, stimulating the exploration of different solution paths.
2. Skills such as decomposition and pattern recognition encouraged students to classify problems into distinct categories and attempt multiple approaches.
3. Group discussions exposed students to diverse viewpoints, broadening their flexibility in idea generation.

Originality:

The average originality score increased from 2.35 to 4.94, a gain of 2.59 points (110.21%). The Wilcoxon signed-rank test showed this improvement to be highly significant ($Z = -3.547$, $p < 0.001$). This was one of the strongest effects observed, indicating that the intervention effectively enhanced students' ability to generate novel and unique ideas. Explanations include:

1. The project's emphasis on designing novel solutions encouraged students to break conventional thinking patterns and generate unique ideas.
2. Through iterative prototyping and peer feedback, students refined their ideas, leading to more creative and original outputs.

Elaboration:

The average elaboration score rose from 2.94 to 5.59, an increase of 2.65 points (90.14%). The Wilcoxon signed-rank test indicated a highly significant improvement ($Z = -3.546$, $p < 0.001$). This demonstrates that students gained the ability to enrich and refine their ideas with greater detail. Possible reasons include:

1. Activities such as refining system designs (e.g., adding details to visual layouts or improving algorithm parameters) directly targeted elaboration skills.
2. Students received ongoing feedback, which likely motivated them to add depth and detail to their ideas.

In designing the product recognition module, one group initially created a basic recognition system. Through group discussions and peer feedback, they added features like error notifications and real-time feedback for customers. This iterative process significantly

TABLE 4 Descriptive statistics and Shapiro–Wilk normality test results ($N = 17$).

Variable	N	Avg.	SD	Skewness	Kurtosis	Shapiro–Wilk test	
						W	p
FluencyPretest	17	6.882	2.342	−0.171	−0.697	0.962	0.677
FlexibilityPretest	17	4.059	1.952	0.536	−1.482	0.815	0.003**
OriginalityPretest	17	2.353	1.539	1.422	1.089	0.758	0.001**
ElaborationPretest	17	2.941	2.164	1.553	2.693	0.833	0.006**
RedefinitionPretest	17	2.471	1.505	0.687	−0.874	0.837	0.007**
TotalPretest	17	18.706	6.789	0.397	−0.855	0.948	0.419
FluencyPosttest	17	7.706	2.443	0.329	−0.451	0.945	0.379
FlexibilityPosttest	17	5.824	2.481	0.089	−1.382	0.918	0.138
OriginalityPosttest	17	4.941	1.478	−0.282	−1.456	0.848	0.010**
ElaborationPosttest	17	5.588	2.293	0.647	−0.842	0.891	0.047*
RedefinitionPosttest	17	3.471	1.875	1.277	0.949	0.794	0.002**
TotalPosttest	17	27.529	7.203	−0.478	−1.168	0.895	0.056

*$p < 0.05$, **$p < 0.01$.

TABLE 5 Wilcoxon signed-rank test results for pre-test and post-test differences ($N = 17$).

Option	Fluency posttest – fluency pretest	Flexibility posttest – flexibility pretest	Originality posttest – originality pretest	Elaboration posttest – elaboration pretest	Redefinition posttest – redefinition pretest	Total posttest – total pretest
Z	−2.435[b]	−2.993[b]	−3.547[b]	−3.546[b]	−2.516[b]	−3.626[b]
Asymp. Sig. (2-tailed)	0.015	0.003	0	0	0.012	0

a. Wilcoxon signed-rank test. b. Based on negative ranks.

improved their elaboration score by 90.03%. The case highlights how iterative design and peer feedback fostered students' ability to refine and expand their ideas.

Redefinition:

The average redefinition score increased from 2.47 to 3.47, a gain of 1.00 point (40.49%). The Wilcoxon signed-rank test confirmed the significance of this improvement ($Z = -2.516$, $p = 0.012$). Redefinition reflects students' ability to reinterpret or transform given concepts, and its growth suggests the project helped expand this aspect of creativity. Possible explanations include:

1. Redefining problems often requires advanced cognitive skills and a deeper understanding of the context, which may be difficult to significantly enhance within a short intervention.
2. While the project included tasks that encouraged redefinition (e.g., troubleshooting and optimizing system designs), this dimension may require more targeted activities over a longer period.

As shown in Table 6, the pre-test and post-test scores for all five dimensions exhibited significant positive correlations ($p < 0.01$). The strongest correlation was observed between fluency and elaboration ($r = 0.878$), suggesting that students who were able to generate more ideas also tended to refine those ideas more thoroughly. Correlations for flexibility, originality, and redefinition were slightly lower ($0.60 < r < 0.70$), indicating greater variability in how students developed these aspects of creative thinking. The total score also showed a strong correlation between pre-test and post-test results ($r = 0.808$, $p < 0.001$), reflecting overall consistency in students' performance across the intervention.

The results indicate significant improvements in all dimensions of creative thinking, with the largest gains observed in originality and elaboration. These findings suggest that the "Unmanned Supermarket" project intervention, designed within a PBL framework, effectively supported the development of students' creative thinking, particularly in generating novel ideas and refining them. While fluency and redefinition showed smaller improvements, these dimensions may require longer-term interventions and more targeted activities to achieve substantial growth.

5 Discussion

This study comprehensively analyzed how PBL, integrated with CT elements, supports the development of students' creative thinking across diverse dimensions through the "Unmanned Supermarket" project.

5.1 Key findings and analysis

The results demonstrated a significant improvement in students' overall creative thinking scores, with an average increase of 8.82

TABLE 6 Correlations between pre-test and post-test scores for each dimension of creative thinking.

Variable	Fluency pretest	Flexibility pretest	Originality pretest	Elaboration pretest	Redefinition pretest	Total pretest
Fluency posttest	0.878**	0.541*	0.262	0.197	0.278	0.642**
Flexibility posttest	0.502*	0.648**	0.590*	0.440	0.275	0.694**
Originality posttest	0.233	0.326	0.669**	0.351	0.154	0.472
Elaboration posttest	−0.056	0.285	0.309	0.839**	0.331	0.474
Redefinition posttest	0.184	0.334	0.112	0.192	0.692**	0.399
Total posttest	0.548*	0.651**	0.557*	0.607**	0.506*	0.808**

*$p < 0.05$, **$p < 0.01$.

points. The Wilcoxon signed-rank test confirmed that this difference was statistically significant ($Z = -3.622$, $p < 0.001$). The most notable improvements were observed in the dimensions of originality and elaboration, while fluency and redefinition showed smaller but still significant gains. Recent studies highlight that integrating computational thinking (CT) with PBL significantly enhances students' interdisciplinary skills and creative thinking (Zhou and Zhang, 2024). Particularly in real-world problem-solving, students use CT techniques like decomposition and abstraction to generate innovative solutions within the PBL framework. This further supports the effectiveness of the "Unmanned Supermarket" project in promoting different dimensions of creative thinking. Although the study involved only 17 students and the intervention lasted just 4 weeks, these findings offer preliminary empirical support for the potential of integrating PBL and CT to enhance creative thinking, particularly in specific dimensions.

It is important to emphasize that the purpose of this study is not to draw broad generalizations but to provide directions for future research. As Shadish et al. (2002) highlighted, small-sample pilot studies can serve as an essential foundation for exploratory research, offering a basis for future confirmatory studies. Furthermore, although this study did not directly measure CT abilities, the inclusion of CT elements (e.g., decomposition, abstraction, and algorithm design) in the task design allows for an indirect assessment of their potential role in fostering creative thinking.

5.2 Impact of problem-based learning combined with computational thinking on the five dimensions of creative thinking

In-depth analysis reveals that the integration of computational thinking (CT) elements within a problem-based learning (PBL) framework has varying impacts on different dimensions of creative thinking:

1. Significant improvements in originality and elaboration

Originality scores increased from 2.35 in the pre-test to 4.94 in the post-test, representing a 110.13% improvement. The Wilcoxon signed-rank test confirmed that this gain was statistically significant ($Z = -3.547$, $p < 0.001$). Similarly, elaboration scores rose from 2.94 to 5.59, a 90.03% improvement, which was also highly significant ($Z = -3.546$, $p < 0.001$). These results indicate that the "Unmanned Supermarket" project encouraged students to break traditional thinking patterns, propose unique ideas, and refine these into detailed and actionable plans. This aligns with Brennan and Resnick's (2012) argument that CT serves as a tool for fostering innovative problem-solving. In the redefinition tasks, students were asked to rename "unmanned supermarket" and propose new concepts. One group suggested the name "Smart Living Hub," redefining the supermarket as a multifunctional space integrating shopping, entertainment, and education. This innovative approach contributed to the observed 40.49% improvement in redefinition scores and highlights the potential of real-world scenarios to stimulate conceptual creativity.

CT elements such as problem decomposition and algorithm design supported students in systematically addressing complex problems, while the iterative feedback and peer evaluation embedded in the PBL framework further stimulated their creative potential (Grover and Pea, 2013). For instance, during the development of the payment module, students collaboratively refined their ideas, such as using facial recognition to recommend personalized products, which significantly enhanced their originality and elaboration skills.

2. Notable improvement in flexibility

Flexibility scores increased from 4.06 in the pre-test to 5.82 in the post-test, representing a 43.47% improvement. The Wilcoxon signed-rank test confirmed that this gain was statistically significant ($Z = -2.993$, $p = 0.003$). The PBL project, which emphasized task decomposition and multi-perspective analysis, encouraged students to approach problems from different angles and adapt their strategies to diverse contexts. These findings are consistent with Hidayat and Prabawanto's (2018) view that flexibility plays a crucial role in addressing complex problems.

3. Limited improvements in fluency and redefinition:

Fluency scores improved by only 11.98%, while redefinition scores increased by 40.49%. The relatively smaller gains in fluency and redefinition may be attributed to the short duration of the intervention. Shute et al. (2017) found that these dimensions require longer-term interventions and more diverse task designs to show significant improvement. The four-week intervention in this study may have been insufficient to fully develop these dimensions. Future research could extend the intervention duration and include more open-ended tasks to enhance fluency and redefinition. The limited improvement in fluency may be attributed to the relatively short duration of the intervention or the lack of targeted training in generating a high volume of ideas. Similarly, redefinition, which often requires more advanced cognitive skills, may need longer-term interventions to observe significant growth. These findings suggest that while PBL and CT integration effectively enhance certain dimensions of creative thinking, broader and more sustained interventions are necessary for comprehensive improvement (Torrance, 1988).

These findings suggest that integrating CT elements into PBL activities can support the development of students' creative thinking, particularly in the dimensions of originality and elaboration. However, fluency and redefinition appear to require more sustained and diverse interventions to achieve significant improvements. The results highlight the potential of combining PBL and CT as an effective framework for fostering creative thinking in primary education.

5.3 Implications for educational practice

The findings of this study provide the following specific insights for educational practice:

1. Integrating CT into primary Education Curriculum Design: The results highlight the importance of integrating CT elements into PBL tasks within the primary education curriculum. Upper primary school students are at a critical stage in the development of logical thinking and abstract reasoning abilities, as suggested by Piaget (1952) theory, making them well-suited for engaging in structured PBL activities that incorporate CT skills. PBL provides an effective framework for integrating CT skills, allowing students to solve real-world problems while engaging in interdisciplinary projects. CT education can be combined with existing school subjects (e.g., mathematics and science) to create an interdisciplinary learning model, further enhancing students' motivation to learn.
2. Focusing on Developing Originality and Elaboration Skills: The findings suggest that PBL tasks incorporating CT elements are particularly effective in supporting the development of originality and elaboration skills. Teachers can design open-ended tasks that encourage students to break away from traditional thinking patterns, propose innovative solutions, and refine their ideas through iterative testing and reflection. Open-ended task designs (e.g., "Design a Future Supermarket") can provide students with more autonomy and exploration opportunities, further stimulating their creativity.
3. Educational practices should incorporate multi-semester PBL projects that provide students with opportunities to engage in diverse application scenarios, enabling them to redefine problems and adapt their thinking across different contexts. Multi-semester, continuous PBL projects or cross-grade interdisciplinary designs can help students gain a deeper understanding of core CT elements, such as abstraction and pattern recognition, while fostering their ability to redefine problems creatively. Diverse situational tasks (e.g., unmanned retail, intelligent transportation) can encourage students to redefine problems from different perspectives and guide them to find innovative solutions in complex contexts.
4. Future research should incorporate direct measurement tools for CT abilities, explore the role of specific PBL task designs, and employ experimental designs with control groups to more precisely analyze the combined effects of PBL and CT elements on creative thinking.

5.4 Comparison with existing studies

The results of this study are consistent with the view proposed by Wing (2006), who stated that CT can promote problem-solving and innovation. Additionally, this study supports Brennan and Resnick's (2012) view that CT serves as a tool and medium for facilitating creativity and innovation within structured learning environments, such as PBL tasks. Unlike Runco (2014) who mainly focused on creativity in the fields of art and language, this study highlights the potential of STEM education, particularly when integrating computational thinking (CT) elements into PBL, to support the development of creative thinking in primary education.

This study found that students demonstrated significant improvements in creative thinking across various dimensions and overall, which aligns with Wing (2006) view that computational thinking (CT) elements, such as problem decomposition and algorithmic thinking, can support problem-solving and innovation when embedded within structured learning tasks like PBL. This study provides further empirical data supporting the integration of CT elements into PBL frameworks, particularly for upper-grade primary school students, highlighting the potential of combining CT and PBL to foster creative thinking. The results of this study are consistent with constructivist learning theory proposed by Papert (1980); that is, students learn by designing and creating meaningful projects.

In general, this study supplements and expands the existing literature and research as follows:

1. This study explores how integrating computational thinking (CT) elements into problem-based learning (PBL) tasks can support the development of students' creative thinking skills.
2. It addresses a gap in existing research on the intersection of CT, PBL, and creative thinking in the upper grades of primary school, providing a foundation for further studies in this age group.
3. Through the "unmanned supermarket" project, the abstract concept of CT is combined with specific situations in real life.

In summary, this study investigated how PBL tasks enriched with CT elements can support the development of students' creative thinking. It provides new directions and perspectives for future research on the integration of CT and PBL in primary education. Although this study has certain limitations, such as the absence of direct CT measurement, the results provide a valuable empirical basis for understanding how integrating CT elements within PBL tasks can support the development of creative thinking.

6 Conclusions and limitations

6.1 Conclusion

This study provides empirical support for Grover and Pea's (2018) view of CT as a core competence, extending this theory by exploring how integrating CT elements into PBL environments can support the development of creative thinking. This finding is consistent with Beghetto and Kaufman's (2013) view that creativity develops in specific learning environments. Through well-designed PBL interventions that incorporate CT elements, educators can cultivate a generation of learners equipped with both CT skills and creative thinking, laying the foundation for their future success in an increasingly digital and innovation-driven society. Future research and practice should continue to explore how to more effectively combine CT education with creative thinking cultivation to cope with the rapidly changing technological environment and social needs (Honey et al., 2014).

This study provides preliminary evidence that PBL interventions, such as the 'Unmanned Supermarket' project, can enhance students' creative thinking across multiple dimensions by integrating CT elements like problem decomposition and algorithm design into real-world problem-solving tasks. However, the absence of direct measurement of CT limits the ability to draw definitive conclusions about the role of CT in these improvements, emphasizing the need for future studies to explore this relationship with more robust methodologies. While the intervention was designed to integrate key CT elements, such as abstraction and algorithm design, the observed creativity gains could also be attributed to other factors, such as collaborative learning, teacher guidance, or the overall structure of the PBL framework. Future studies should incorporate direct CT assessments to establish a clearer causal relationship between CT, PBL, and creative thinking.

Through the design and implementation of the "Unmanned Supermarket" project, this study explored the impact of PBL instruction on students' creative thinking abilities and provided the following contributions:

1. Relationship Between CT and Creative Thinking: This study is one of the first to explore how integrating CT elements into PBL frameworks can positively influence different dimensions of creative thinking among upper primary school students.
2. PBL-Based CT Curriculum Design: Through the "Unmanned Supermarket" project, this study demonstrated how the PBL model can effectively integrate CT elements to support students' creative thinking development, providing a practical example for STEM education in upper primary grades. It provides a practical example for STEM education in upper primary grades.

As a model for integrating CT elements into PBL to support students' creative thinking, this study explores how the application of core CT elements, such as problem decomposition and algorithm design, within a PBL framework can facilitate the development of creative thinking skills. This preliminary framework offers a new perspective for future research on integrating CT elements into PBL to foster creative thinking, particularly in the context of STEM education. To evaluate creative thinking abilities across different dimensions, this study developed a new measurement tool that combines traditional creative thinking tests with the CT context and the "Unmanned Supermarket" scenarios. This innovative approach provides new design ideas for evaluating creative thinking in educational interventions that integrate CT and PBL. The student designs in the "Unmanned Supermarket" project provide clear evidence that computational thinking (e.g., problem decomposition, abstraction, and algorithmic design) facilitates the development of creative thinking, particularly in originality and elaboration. For instance, students' innovative payment systems and product recognition modules demonstrate their ability to connect abstract CT concepts to real-world solutions. These results underscore the effectiveness of PBL combined with CT in fostering a dynamic and creative learning environment.

The "unmanned supermarket" project designed in this study provides empirical evidence for integrating CT elements into PBL activities for senior primary school students. It highlights how the PBL teaching model can effectively bridge abstract CT concepts with specific real-life scenarios, fostering both creative problem-solving and critical thinking skills. This study proposes that, through meaningful PBL activities that incorporate CT elements, students' creative thinking abilities can be effectively cultivated, offering a new direction for fostering talents equipped to thrive in the digital age. It is recommended to develop evaluation tools for computational and creative thinking abilities suitable for primary school students and to encourage the use of diversified evaluation methods in order to effectively and comprehensively evaluate students' various thinking abilities.

6.2 Limitations of the study

6.2.1 Measurement tool validation

One of the primary limitations of this study is the reliance on a single expert for validating the creative thinking measurement tool. While the expert provided valuable feedback, the absence of a broader validation process limits the generalizability and scientific rigor of the tool. This study acknowledges the need for future research to incorporate:

1. Larger-Scale Validation: Conducting reliability and validity analyses with larger sample sizes.
2. Diverse Expert Review: Engaging multiple experts from different fields to ensure a comprehensive evaluation of the tool.
3. Direct Comparisons with Established Tools: Comparing the tool's performance with widely used creativity assessments such as the TTCT to establish its reliability and effectiveness.

6.2.2 Sample size and representativeness

This study was conducted with only 17 students from an primary school in Shenzhen. The small sample size, along with geographical and age constraints, limits the generalizability of the findings.

6.2.3 Absence of direct measurement of CT

A major limitation of this study is the absence of direct measurement of CT. While the intervention was designed to embed CT elements, such as problem decomposition, pattern recognition, and debugging, the lack of standardized CT assessments or performance-based tasks restricts the ability to validate CT's specific contribution to the observed improvements in creative thinking. Future research should incorporate direct CT assessment tools, such as standardized tests or authentic performance tasks, to establish a clearer understanding of the relationship between CT and creative thinking. The single-group pre-test–post-test design limits the ability to control for other instructional variables, such as teacher guidance or peer collaboration, which may have contributed to the results.

6.2.4 Short-term effects of the intervention

The intervention period in this study was relatively short (4 weeks), which limits the ability to observe the sustained impact of integrating CT elements into PBL activities on the development of creative thinking. Creative thinking, particularly dimensions like flexibility and redefinition, often requires extended practice and exposure to diverse problem-solving contexts. Longer-term interventions are necessary to determine whether the observed improvements are maintained or further developed over time.

6.3 Suggestions for future research

To further enhance the applicability and value of this study, future research should explore how PBL integrated with CT can support the development of creative thinking in diverse educational and cultural contexts. Building on the findings and limitations of this study, specific suggestions for future research include:

1. Adapting PBL and CT Projects to Cultural and Technological Contexts: The "Unmanned Supermarket" project could be adapted to align with local cultural and technological norms, making the learning experience more meaningful and relevant to students in different regions. Simplified or unplugged versions of CT activities could be developed for schools with limited technological infrastructure, which ensures accessibility and scalability of PBL-CT interventions.
2. Integration into Diverse Educational Systems: Subsequent investigations should examine strategies for embedding CT pedagogical approaches within heterogeneous educational systems, particularly those constrained by rigid curricular structures or technological resource limitations. For systems governed by rigid curricula, PBL-CT methodologies might be systematically incorporated through alignment with existing subject requirements.
3. Expanding the Scope to Different Age Groups and Interdisciplinary Subjects: Developmental scaling of the PBL-CT model to other age groups, such as middle or high school students, to investigate how ontogenetic variations modulate intervention efficacy. Adapt the PBL-CT approach to interdisciplinary subjects, such as arts, humanities, or social sciences, to demonstrate its versatility and broader applications in fostering creative thinking.
4. Designing Longitudinal and Comparative Studies: Implement longitudinal studies to assess the sustained influence of PBL-CT interventions on creative thinking, tracking developmental trends across different age groups. Include control groups and employ randomized experimental designs to better isolate the influence of PBL-CT on creative thinking and controlling for confounding factors, such as maturation or testing effects.
5. Developing Comprehensive Assessment Tools for Creative Thinking: While this study primarily relied on quantitative scoring to evaluate creative thinking, future research could incorporate qualitative methods such as student reflection reports, project presentations, and peer evaluations to provide a more comprehensive understanding of students' creative thinking processes. Develop assessment tools tailored to specific PBL-CT contexts, focusing on how students apply CT skills (e.g., decomposition, pattern recognition) to solve creative tasks.
6. Clarifying the Role of CT within PBL Frameworks: Although this study indirectly validated the potential role of CT skills (e.g., task decomposition, abstraction) in supporting creative thinking, future research should incorporate direct measurement tools for CT abilities, such as programming assessments or performance-based activities, to establish clearer links between CT and creative thinking. Investigate how specific CT skills are activated and applied in PBL scenarios, identifying key moments where CT contributes to creative problem-solving. Explore how variations in CT integration (e.g., depth of programming tasks, level of algorithmic thinking) influence different dimensions of creative thinking, such as originality or elaboration.
7. Examining the Interaction Between CT, PBL, and Creative Thinking: Conduct cross-cultural comparisons to examine how cultural factors influence the relationship between PBL, CT, and creative thinking. Partner with researchers from different countries and regions to explore how PBL-CT interventions can be adapted to diverse educational contexts, providing a global perspective on their effectiveness.

By addressing these limitations and exploring the replication of this study in diverse educational contexts, future research can build on the findings to advance the understanding of how PBL integrated with CT supports creative thinking. These efforts will not only enhance the theoretical foundation of PBL-CT models but also provide practical guidance for educators seeking to foster creativity and problem-solving skills in the 21st century.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving humans were approved by The University of Hong Kong Faculty of Education. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

WJ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. GW: Project administration, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1625105/full#supplementary-material

References

Abraham, A. (2016). Gender and creativity: an overview of psychological and neuroscientific literature. *Brain Imaging Behav.* 10, 609–618. doi: 10.1007/s11682-015-9410-8

Amabile, T. M., and Pratt, M. G. (2016). The dynamic componential model of creativity and innovation in organizations: making progress, making meaning. *Res. Organ. Behav.* 36, 157–183. doi: 10.1016/j.riob.2016.10.001

Angeli, C., Voogt, J., Fluck, A., Webb, M., Cox, M., Malyn-Smith, J., et al. (2016). A k-6 computational thinking curriculum framework: implications for teacher knowledge. *Educ. Technol. Soc.* 19, 47–57.

Anwar, M. N., and Aness, M. (2012). An examination of the relationship between creative thinking and academic achievements of secondary school students. *Int. Interdiscip. J. Educ.* 1, 1–4. Available at: https://search.emarefa.net/detail/BIM-666691

Ausubel, D. P. (1968). Educational psychology: A cognitive view. New York: Holt, Rinehart and Winston.

Beghetto, R. A., and Kaufman, J. C. (2009). Do we all have multicreative potential? *ZDM Math. Educ.* 41, 39–44. doi: 10.1007/s11858-008-0143-7

Beghetto, R. A., and Kaufman, J. C. (2013). Fundamentals of creativity. *Educ. Psychol. Rev.* 25, 3–11. Available at: https://www.researchgate.net/publication/261797704_Fundamentals_of_Creativity

Beghetto, R. A., and Kaufman, J. C. (2014). Classroom contexts for creativity. *High Abil. Stud.* 25, 53–69. doi: 10.1080/13598139.2014.905247

Bell, S. (2010). Project-based learning for the 21st century: skills for the future. *Clear. House* 83, 39–43. doi: 10.1080/00098650903505415

Bers, M. U. (2020). Coding as a playground: Programming and computational thinking in the early childhood classroom. New York: Routledge.

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., and Palincsar, A. (1991). Motivating project-based learning: sustaining the doing, supporting the learning. *Educ. Psychol.* 26, 369–398. doi: 10.1080/00461520.1991.9653139

Brennan, K., and Resnick, M. (2012). "New frameworks for studying and assessing the development of computational thinking" in Proceedings of the 2012 annual meeting of the American Educational Research Association, Vancouver, Canada.

Capraro, R. M., Capraro, M. M., and Morgan, J. R.. (2013). STEM project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach (2nd ed.). Rotterdam: Sense Publishers. doi: 10.1007/978-94-6209-143-6

Clements, D.H., and Sarama, J. (2020). Learning and Teaching Early Math: The Learning Trajectories Approach (3rd ed.). New York: Routledge. doi: 10.4324/9781003083528

Cohen, L., Manion, L., and Morrison, K. (2018). Research methods in education. *8th* Edn. London: Routledge. doi: 10.4324/9781315456539

Cook, T. D., and Campbell, D. T. (1979). Quasi-experimentation: Design & analysis issues for field settings. Longon: Houghton Mifflin.

CPC Central Committee and State Council (2019) China's education modernization 2035 CPC Central Committee and State Council

Craft, A. (2011). Creativity and education futures: Learning in a digital age. Stoke-on-Trent: Trentham Books.

Cropley, D. H. (2015). Creativity in engineering. Novel solutions to complex problems. San Diego: Elsevier Academic Press. doi: 10.1016/B978-0-12-800225-4.00002-1

Cropley, A. J. (2020). Creativity-focused technology education in the age of industry 4.0. *J. Educ. Work.* 33, 548–562. doi: 10.1080/10400419.2020.1751546

DeHaan, R. L. (2009). Teaching creativity and inventive problem solving in science. *CBE Life Sci. Educ.* 8, 172–181. doi: 10.1187/cbe.08-12-0081

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Dimitrov, D. M., and Rumrill, P. D.Jr. (2003). Pretest-posttest designs and measurement of change. *Work* 20, 159–165. doi: 10.3233/WOR-2003-00285

English, L. D. (2016). STEM education k-12: perspectives on integration. *Int. J. STEM Educ.* 3:3. doi: 10.1186/s40594-016-0036-1

Etikan, I., Musa, S. A., and Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. *Am. J. Theor. Appl. Stat.* 5, 1–4. doi: 10.11648/j.ajtas.20160501.11

Feldman, D. H. (2003). "Cognitive development in childhood: a contemporary perspective" in Handbook of psychology. ed. I. B. Weiner (Hoboken, NJ: Wiley), 195–210.

Grover, S., and Pea, R. (2013). Computational thinking in K–12: a review of the state of the field. *Educ. Res.* 42, 38–43. doi: 10.3102/0013189X12463051

Grover, S., and Pea, R. (2018). "Computational thinking: a competency whose time has come" in Computer science education: Perspectives on teaching and learning in school. eds. S. Sentance, E. Barendsen and C. Schulte (London: Bloomsbury Academic), 19–37. Available at: https://www.researchgate.net/publication/322104135_Computational_Thinking_A_Competency_Whose_Time_Has_Come

Guilford, J. P. (1967). The nature of human intelligence. New York: McGraw-Hill.

Hennessey, B. A., and Amabile, T. M. (2010). Creativity. *Annu. Rev. Psychol.* 61, 569–598. doi: 10.1146/annurev.psych.093008.100416

Hidayat, W., and Prabawanto, S. (2018). Improving students' creative mathematical reasoning ability through adversity quotient and argument-driven inquiry learning. *J. Phys. Conf. Ser.* 948:012005. doi: 10.1088/1742-6596/948/1/012005

Honey, M., Pearson, G., and Schweingruber, H. (Eds.) (2014). STEM integration in K-12 education: Status, prospects, and an agenda for research. Washington, DC: National Academies Press. doi: 10.17226/18612

Inman, J. J., and Nikolova, H. (2017). Shopper-facing retail technology: a retailer adoption decision framework incorporating shopper attitudes and privacy concerns. *J. Retail.* 93, 7–28. doi: 10.1016/j.jretai.2016.12.006

Kafai, Y. B., and Proctor, C. (2021). A revaluation of computational thinking in K–12 education: moving toward computational literacies. *Educ. Res.* 51, 146–151. doi: 10.3102/0013189X211057904

Kelley, T. R., and Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *Int. J. STEM Educ.* 3:11. doi: 10.1186/s40594-016-0046-z

Kong, S. C., and Abelson, H. (Eds.) (2019). Computational thinking education. Singapore: Springer. doi: 10.1007/978-981-13-6528-7

Krajcik, J. S., and Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (R. K. Sawyer Ed.), The Cambridge handbook of the learning sciences (317–334). Cambridge: Cambridge University Press.

Liu, Z., Gearty, Z., Richard, E., Orrill, C. H., Kayumova, S., and Balasubramanian, R. (2024). Bringing computational thinking into classrooms: a systematic review on supporting teachers in integrating computational thinking into K-12 classrooms. *IJ STEM Ed* 11:51. doi: 10.1186/s40594-024-00510-6

Lombard, K., and Grosser, M. (2008). Critical thinking: are the ideals of OBE failing us or are we failing the ideals of OBE? *S. Afr. J. Educ.* 28, 561–580.

Milgram, R. M., and Milgram, N. A. (1976). Creative thinking and creative performance in Israeli students. *J. Educ. Psychol.* 68, 255–259. doi: 10.1037/h0079959

Ministry of Education of the People's Republic of China (2018). Education informatization 2.0 action plan. Beijing: Ministry of Education of the People's Republic of China.

Mishra, P., and Henriksen, D. (2013). The deep-play research group. A NEW approach to defining and measuring creativity: rethinking technology & creativity in the 21st century. *Tech Trends* 57, 10–13. doi: 10.1007/s11528-013-0685-6

Mishra, P., and Henriksen, D. (2018). Creativity, technology & education: Exploring their convergence. Cham: Springer.

Papert, S. (1980). Mindstorms: Children, computers, and powerful ideas. New York: Basic Books.

Pei, C., Weintrop, D., and Wilensky, U. (2018). Cultivating computational thinking practices and mathematical habits of mind in lattice land. *Math. Teach. Educ. Dev.* 20, 4–31. doi: 10.1080/10986065.2018.1403543

Piaget, J. (1952). The origins of intelligence in children. New York: International Universities Press.

Piaget, J. (1972). Intellectual evolution from adolescence to adulthood. *Hum. Dev.* 15, 1–12. doi: 10.1159/000271225

Piaget, J. (2001). The psychology of intelligence. London: Routledge.

Ramalingam, D., Anderson, P., Duckworth, D., Scoular, C., and Heard, J.. (2020). Creative thinking: Definition and structure. Australian Council for Educational Research. Available online: https://research.acer.edu.au/ar_misc/43 (Accessed February 25, 2020).

Runco, M. A. (2014). Creativity: Theories and themes: Research, development, and practice. San Diego: Elsevier.

Runco, M. A., and Acar, S. (2012). Divergent thinking as an indicator of creative potential. *Creat. Res. J.* 24, 66–75. doi: 10.1080/10400419.2012.652929

Runco, M. A., and Jaeger, G. J. (2012). The standard definition of creativity. *Creat. Res. J.* 24, 92–96. doi: 10.1080/10400419.2012.650092

Sawyer, R. K. (2018). The future of learning: Grounding educational innovation in the learning sciences. Cambridge: Cambridge University Press.

Schmidt, H. G. (1983). Problem-based learning-rationale and description. *Med. Educ.* 17, 11–16. doi: 10.1111/j.1365-2923.1983.tb01086.x

Shadish, W. R., Cook, T. D., and Campbell, D. T. (2002). Experimental and quasi-experimental designs for generalized causal inference. Boston: Houghton Mifflin.

Shute, V. J., Sun, C., and Asbell-Clarke, J. (2017). Demystifying computational thinking. *Educ. Res. Rev.* 22, 142–158. doi: 10.1016/j.edurev.2017.09.003

Siswono, T. Y. E. (2011). Level of student's creative thinking in classroom mathematics. *Int. J. Math. Educ. Sci. Technol.* 42, 227–241. doi: 10.1080/0020739X.2010.519796

Sternberg, R. J., and Lubart, T. I. (1999). "The concept of creativity: prospects and paradigms" in Handbook of creativity. ed. R. J. Sternberg (Cambridge: Cambridge University Press), 3–15.

Szymanski, G., Stanisławski, R., and Boniecki, P. (2021). The role of artificial intelligence in the unmanned stores sector. *Eur. Res. Stud. J.* 24, 1135–1154.

Torrance, E. P. (1966). The Torrance tests of creative thinking-norms-technical manual research edition-verbal tests, forms A and B-figural tests, forms A and B. Princeton, NJ: Personnel Press.

Torrance, E. P. (1968). A longitudinal examination of the fourth grade slump in creativity. *Gift. Child Q.* 12, 195–199. doi: 10.1177/001698626801200401

Torrance, E. P. (1988). The nature of creativity as manifest in its testing. R. J. Sternberg (Ed.), The nature of creativity (pp. 43–75). Cambridge: Cambridge University Press.

Torrance, E. P. Torrance tests of creative thinking (TTCT) [Database record]. Washington, DC: APA PsycTests. doi: 10.1037/t05532-000

UNESCO. (2019). Beijing consensus on artificial intelligence and education. UNESCO.

Wagner, T. (2012). Creating innovators: The making of young people who will change the world. New York: Schuster.

Wing, J. (2006). Computational thinking. *Commun. ACM* 49, 33–35. doi: 10.1145/1118178.1118215

Woltering, V., Herrler, A., Spitzer, K., and Spreckelsen, C. (2009). Blended learning positively affects students' satisfaction and the role of the tutor in the problem-based learning process: results of a mixed-method evaluation. *Adv. Health Sci. Educ. Theory Pract.* 14, 725–738. doi: 10.1007/s10459-009-9154-6

Yadav, A., Hong, H., and Stephenson, C. (2016). Computational thinking for all: pedagogical approaches to embedding 21st century problem solving in K-12 classrooms. *Tech Trends* 60, 565–568. doi: 10.1007/s11528-016-0087-7

Zhou, C., and Zhang, W. (2024). Computational thinking (CT) towards creative action: developing a project-based instructional taxonomy (PBIT) in AI education. *Educ. Sci.* 14:134. doi: 10.3390/educsci14020134