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Computational Thinking and 4E Cognition in Mathematics Education: Toward an Embodied and Situated Framework for Learning

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Abstract

Computational thinking (CT) has become a major priority across educational systems worldwide, particularly in mathematics and science curricula. At the same time, theoretical developments in cognitive science have unsettled the longstanding view of cognition as purely internal and symbolic. The 4E cognition framework—encompassing embodied, embedded, enacted, and extended cognition—proposes instead that thinking arises through the dynamic interplay among brain, body, tools, and environment. Research in mathematics education has increasingly supported this view: gestures, bodily movement, material engagement, digital technologies, and social participation are not supplementary aids to mathematical reasoning but constitutive dimensions of it. This paper examines how computational thinking and 4E cognition can be brought into productive dialogue within mathematics education. Drawing on peer-reviewed research and key theoretical contributions, it reconceptualizes core CT practices—including abstraction, decomposition, algorithmic reasoning, pattern recognition, and debugging—through embodied and situated lenses. Pedagogical implications are developed across several domains: classroom instruction, digital tool design, embodied learning environments, teacher education, and curriculum development. The paper argues that integrating CT with 4E cognition yields a more comprehensive framework for mathematics learning, one that connects symbolic reasoning with bodily action, social interaction, and technological mediation. Such integration moves decisively beyond coding-centred interpretations of CT and opens space for richer forms of mathematical understanding and problem-solving.

Keywords: Computational Thinking, 4E Cognition, Embodied Cognition, Mathematics Education, Computational Literacy, Embodied Learning

1. Introduction

Throughout history, only a few ideas have reshaped educational discourse as quickly as computational thinking. Since Wing's (2006) influential argument that computational reasoning constitutes a fundamental literacy for all citizens—not only for computer scientists—the concept has spread rapidly through school curricula, teacher education programmes, and national policy frameworks. Definitions vary across the literature, but CT is broadly understood to encompass practices such as abstraction, decomposition, algorithmic thinking, pattern recognition, modeling, simulation, and debugging (Brennan & Resnick, 2012; Grover & Pea, 2013).

Mathematics education has emerged as a particularly significant site for CT integration. Mathematical and computational reasoning share important epistemic terrain: both rely on pattern recognition, symbolic representation, logical sequencing, and the construction of formal models. Researchers have therefore argued that CT can deepen mathematical understanding while mathematical thinking provides a conceptual substrate for computational reasoning (Weintrop et al., 2016). This relationship is not merely additive; the two domains can mutually enrich each other in ways that remain underexplored.

Simultaneously, cognitive science has undergone a substantial reorientation. Classical cognitivism modelled the mind as a computational device that manipulates internal symbols according to formal rules. The 4E cognition framework—developed across works such as Varela, Thompson, and Rosch's (1991) foundational The Embodied Mind and Hutchins's (1995) Cognition in the Wild—challenges this picture fundamentally. Cognition, on this account, is embodied, embedded, enacted, and extended: it emerges through interactions among bodily action, cultural environments, social practices, and external tools, rather than occurring solely within the individual mind.

These developments carry significant implications for mathematics education. A growing body of research documents the role of gesture, movement, manipulative engagement, and digital interaction in mathematical learning (Abrahamson, 2014; Alibali & Nathan, 2012). Rather than treating the body as merely a vehicle for transmitting mental content, embodied cognition research argues that bodily action is partially constitutive of mathematical understanding. Students often express mathematical reasoning through gesture before they can articulate it symbolically (Goldin-Meadow, 2014), a finding with profound consequences for how we design, enact, and assess mathematics instruction.

Despite the parallel growth of CT research and embodied cognition research, relatively little scholarship has systematically connected the two within mathematics education. CT frameworks have tended to retain cognitivist assumptions, treating computational reasoning as mental problem-solving and coding as its primary expression. Meanwhile, 4E cognition foregrounds precisely the situated, material, and interactional dimensions that such frameworks overlook. This paper argues that bringing CT and 4E cognition into sustained dialogue produces a richer theoretical framework for mathematics learning and more defensible principles for pedagogical practice.

2. Computational Thinking in Mathematics Education

Computational thinking is a multidimensional construct whose meaning has shifted considerably since its contemporary popularisation. Its intellectual lineage in education runs through Papert's (1980) pioneering work with the LOGO programming environment, in which he demonstrated that programming could function as a medium for children's mathematical thought. Papert's constructionist thesis—that learners develop deeper understanding by constructing publicly shareable artefacts—positioned the computer not as an instructional delivery system but as what he called an 'object-to-think-with.' This early formulation already anticipated several themes central to extended cognition theory.

Wing (2006) reinvigorated interest in CT by framing it as a universal cognitive skill comparable to reading, writing, and arithmetic. Her account emphasised abstraction, automation, and the identification of computational solutions to problems across diverse domains. Subsequent scholars elaborated and contested this formulation. Brennan and Resnick (2012) distinguished between computational concepts (loops, variables, conditionals), computational practices (debugging, iterating, abstracting), and computational perspectives (connecting, questioning, expressing)—a framework that acknowledged the social and creative dimensions of CT. Grover and Pea (2013), in a survey of CT research in K-12 contexts, identified abstraction, generalisation, and algorithmic thinking as core competencies, while noting persistent definitional ambiguity.

For mathematics education specifically, Weintrop et al. (2016) proposed a taxonomy of CT practices organised around four clusters: data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices. This taxonomy usefully extended CT beyond programming syntax to encompass epistemic practices common across mathematical and scientific domains. Research following this framework has shown that environments such as Scratch, NetLogo, and robotics platforms can support students' exploration of geometric transformations, coordinate systems, sequences, and functions through dynamic computational manipulation (Hoyles & Noss, 2003).

Nevertheless, two persistent criticisms deserve attention. First, CT integration in classrooms often collapses into coding instruction, with insufficient attention to the mathematical concepts that computational activities are meant to illuminate. Second, and more fundamentally, many CT frameworks continue to rely on cognitivist models that treat reasoning as internal information processing. This orientation marginalises the social, material, and embodied dimensions of learning that mathematics education research has increasingly foregrounded. Understanding students' computational reasoning requires attending not only to their symbolic outputs but to the gestures, movements, material interactions, and collaborative exchanges through which that reasoning takes shape.

3. The 4E Cognition Framework

The 4E cognition framework arose as a sustained critique of classical cognitivism and its computational metaphor of mind. Rather than locating cognition inside the skull as the manipulation of internal representations, the 4E view holds that cognitive processes are constitutively shaped by the body, the environment, and social and technological systems. Each of the four dimensions—embodied, embedded, enacted, and extended—captures a distinct aspect of this relational view.

3.1 Embodied Cognition

Embodied cognition holds that cognitive processes are grounded in sensorimotor experience and bodily action. Thinking is not separable from bodily movement; the structure of conceptual understanding reflects patterns of bodily engagement with the world (Wilson, 2002). Within mathematics education, this perspective suggests that gestures, spatial orientation, rhythmic movement, and physical interaction with objects are not decorative accompaniments to reasoning but integral to it. Lakoff and Núñez's (2000) influential argument that mathematical ideas are grounded in embodied metaphors—that arithmetic concepts draw on bodily experiences of combining, separating, and moving along paths—provides a theoretical bridge between embodied cognition and mathematical content.

3.2 Embedded Cognition

Embedded cognition emphasises that thinking always occurs within specific physical, cultural, and social environments that partially constitute it. Cognitive activity cannot be fully understood in abstraction from the contextual structures that shape it. For mathematics education, this means that classroom culture, material organisation, institutional norms, and social practices are not mere background conditions but active contributors to mathematical reasoning. Students learn to think mathematically within specific environments, and those environments matter.

3.3 Enacted Cognition

Enacted cognition, developed most fully by Varela et al. (1991), proposes that cognition arises through active engagement with the world rather than through passive reception or internal computation.

Knowledge is not pre-formed and then retrieved; it is produced through action and interaction. In mathematics education, this principle supports inquiry-based and exploratory pedagogies in which understanding emerges through doing mathematics—constructing, testing, revising, and communicating—rather than receiving pre-formed mathematical content.

3.4 Extended Cognition

Extended cognition, particularly associated with Clark and Chalmers (1998), proposes that cognitive processes may extend beyond the boundaries of the brain and body into external tools, representations, and social systems when those external resources function as constitutive parts of the reasoning process. On this view, a student using a graphing application to explore a function is not simply using a tool; the application is part of the cognitive system through which the mathematical investigation proceeds. This dimension is particularly relevant to understanding CT, given the central role of computational tools in mediating mathematical activity.

Together, the four dimensions of the framework point toward a relational and distributed understanding of cognition that contrasts sharply with individualist and internalist accounts. Recent scholarship in mathematics education has drawn productively on these ideas. Research on gesture (Alibali & Nathan, 2012; Goldin-Meadow, 2014), embodied design (Abrahamson, 2014; Abrahamson & Lindgren, 2014), and technology-mediated learning has collectively demonstrated that mathematical understanding is bound up with bodily, social, and material experience in ways that traditional instructional models fail to capture.

4. Connecting Computational Thinking and 4E Cognition

Bringing computational thinking into dialogue with 4E cognition requires reconceptualising CT practices as situated activities rather than purely mental operations. From a 4E perspective, computational reasoning is distributed across bodies, artefacts, representations, social interactions, and technological systems. Each of the core CT practices takes on new meaning when viewed through this lens.

Algorithmic thinking, conventionally described as the mental construction of step-by-step procedures, can be understood instead as an enactive practice in which sequences are discovered and refined through physical engagement. Research on embodied computational learning environments suggests that students grasp sequencing and loop structures more readily when they physically perform or enact the associated actions before translating them into symbolic code (Kwon, 2025). The understanding does not precede the action; it emerges through it. This is not merely a pedagogical technique but a substantive claim about the nature of algorithmic reasoning.

Pattern recognition similarly benefits from an embodied and embedded reframing. Students typically identify mathematical regularities through visual scanning, gestural tracing, rhythmic engagement, and dynamic interaction with representations—processes that are perceptual and motoric as much as they are logical. Reducing pattern recognition to a cognitive matching operation obscures the sensorimotor activities through which patterns are first perceived and then progressively abstracted.

Abstraction itself, the process of moving from particular instances to general principles, can be understood as a trajectory from embodied experience toward symbolic representation rather than as a purely disembodied operation. Manipulatives, gestures, and dynamic digital tools function as transitional representational systems that allow learners to maintain perceptual-motor engagement with mathematical structure while progressively formalising their understanding. On this account, abstraction is not the abandonment of the body but its gradual transformation into a symbol.

Extended cognition offers particularly important resources for understanding CT because computational activity is so thoroughly tool-mediated. Papert's (1980) constructionist framing anticipated this: when students programme a turtle's movements or construct a simulation, the computational environment participates in the mathematical reasoning rather than merely displaying its results. Programming environments, simulation tools, robotics systems, and graphing software function as cognitive partners in a distributed system of mathematical inquiry.

Recent empirical work supports these theoretical connections. Yeung, Ng, and Zhang (2024) found that young children expressed computational thinking through bodily action and gesture when working with touchscreen mathematics applications, suggesting that CT competence may be rooted in sensorimotor engagement before it achieves formal symbolic expression. Fofang et al. (2021) similarly argued that CT practices are grounded in embodied interaction and situated activity, with coordination among movement, perception, and social participation playing a constitutive role. These findings challenge the assumption that CT development follows a unilinear trajectory from concrete manipulation to abstract symbolic mastery.

The embedded dimension of 4E cognition draws attention to the social and institutional contexts within which CT develops. Hutchins's (1995) analysis of distributed cognition demonstrated that reasoning is regularly distributed across multiple agents and artefacts rather than concentrated within individuals. Computational reasoning in authentic classroom contexts follows similar patterns: students collaborate, share representations, divide cognitive labour, and build on one another's partial solutions. Educational models that focus exclusively on individual CT skill acquisition miss this distributed character.

5. Embodied Learning and Mathematical Understanding

Embodied approaches to mathematics learning have accumulated substantial empirical support over the past few decades. Research consistently shows that mathematical understanding is shaped by gesture, movement, and sensorimotor engagement with representations, not merely by exposure to symbolic content.

The role of gesture in mathematical cognition has been extensively documented. Goldin-Meadow (2014) demonstrated that gestures serve cognitive functions beyond communicative display: they externalise implicit knowledge, reduce working memory demands, and mark conceptual transitions between representational levels. Critically, students' gestures sometimes reveal mathematical understanding that their verbal and written responses do not yet express, suggesting that embodied knowledge precedes its formal articulation. Alibali and Nathan (2012) extended this analysis to teaching practices, showing that teachers' gestures systematically convey mathematical relationships that speech alone cannot fully express and that students draw on these gestural resources in their own reasoning.

Embodied design as an educational research programme has sought to translate these findings into deliberate instructional interventions. Abrahamson (2014) described embodied design as an approach that begins with perceptual-motor activity and progressively introduces formal mathematical language to describe what learners are already doing bodily. In such environments, students manipulate physical or digital objects to produce desired sensory effects, and mathematical concepts emerge as descriptions of those interactions. The body is not an obstacle to abstraction but its starting point.

These principles translate directly to CT contexts. Because computational concepts such as loops, variables, conditionals, and coordinates are highly abstract, embodied entry points may be especially valuable. Kwon et al. (2025) found that augmented reality environments that integrate physical movement with computational tasks improved students' understanding of CT concepts and their computational problem-solving skills. Students who enacted sequencing and loop structures bodily before encountering them symbolically demonstrated more robust conceptual understanding than those who encountered symbolic representations first.

Research on early mathematics education further supports the value of embodied approaches. Way (2024) reviewed evidence indicating that embodied learning modes can meaningfully enhance mathematical understanding across multiple domains in young learners, with bodily interaction, gesture, and movement supporting conceptual development in ways that symbolic instruction alone does not. These findings matter for CT integration because they suggest that computational reasoning need not wait for formal symbolic mastery; it can be cultivated through appropriately designed embodied activity from early in mathematical education.

There are also affective and motivational reasons to attend to embodied learning. Mathematics anxiety and disengagement frequently arise from instruction that makes mathematical concepts feel remote and inaccessible. Embodied and interactive environments can reduce the perceived cognitive distance between learners and mathematical ideas by making abstract relationships perceptually available. Gordon (2021), proposing an integrated model connecting gesture, executive function, and mathematics learning, argued that embodied engagement supports not only conceptual understanding but also self-regulation and motivational engagement—dimensions that are crucial for sustained mathematical development.

6. Digital Technologies, Computational Tools, and Extended Cognition

The extended cognition dimension of 4E cognition has particular salience in an era when digital technologies increasingly mediate mathematical activity. Programming environments, dynamic geometry software, data visualisation platforms, simulation tools, and artificial intelligence applications have transformed what it means to do and learn mathematics. Understanding these transformations requires theoretical resources that extended cognition can provide.

Clark and Chalmers (1998) argued that when an external resource functions reliably, is readily accessible, and is automatically endorsed by the agent, it can legitimately be considered part of that agent's cognitive system. Many of the digital tools that students use in contemporary mathematics classrooms meet these conditions. Dynamic geometry software, such as GeoGebra, does not merely display mathematical objects; it participates in the reasoning through which properties are discovered, conjectures are formed, and relationships are tested. The student-plus-software system constitutes a cognitive unit that neither the student nor the software comprises alone.

Programming environments exemplify this distributed cognition most vividly. When a student writes code to generate a geometric sequence, test a conjecture about prime numbers, or simulate population growth, the reasoning is distributed across the student's intentions, the symbolic structure of the code, the computational processes that execute it, and the visual feedback the environment provides. Understanding this activity only as the student's internal problem-solving misses most of what is actually happening cognitively. Papert (1980) recognised this when he described programming as a medium through which mathematical ideas become tangible and revisable—a form of extended mathematical thinking avant la lettre.

The emergence of generative artificial intelligence introduces new complexities into this picture. AI systems can now participate in mathematical problem-solving, code generation, and conceptual explanation in ways that blur the boundaries between learner cognition and technological mediation still further. Extended cognition frameworks suggest that this is not categorically different from earlier forms of tool-mediated reasoning—calculators, spreadsheets, and computer algebra systems have long participated in mathematical cognition—but it does intensify questions about the nature of mathematical agency, understanding, and assessment that mathematics education must address.

At the same time, extended cognition does not entail that all technology use automatically benefits learning. Poorly designed digital environments can produce procedural dependence without conceptual understanding, or fragment mathematical activity in ways that prevent the development of connected knowledge. The pedagogical challenge is to design technology-mediated experiences that extend cognition in productive directions—supporting exploration, promoting reflection, and fostering the kind of active mathematical engagement that enactive and embodied perspectives recommend.

7. Pedagogical Implications for Mathematics Education

Integrating CT with 4E cognition yields a set of principles that can orient pedagogical practice in mathematics education. These are not isolated techniques but expressions of a coherent theoretical commitment to understanding learning as embodied, situated, and distributed.

First, mathematics instruction should move beyond symbolic presentation and passive reception. Learners need sustained opportunities to engage mathematically through movement, gesture, physical and digital manipulation, collaborative exploration, and design activity. CT instruction should resist reduction to coding syntax and instead situate computational practices within meaningful mathematical inquiry, where abstraction, pattern recognition, and algorithmic reasoning serve genuine epistemic purposes.

Second, classroom environments should actively support embodied interaction. This means incorporating gesture-rich instruction, physical manipulatives, robotics and tangible computing platforms, touchscreen technologies, spatial reasoning tasks, and embodied modelling activities. Research suggests that embodied entry points are especially valuable for abstract concepts—precisely the kind of concepts that CT and formal mathematics both emphasise. Teachers who model mathematical and computational thinking through gesture and physical demonstration provide learners with embodied resources they can recruit in their own reasoning.

Third, CT should be integrated across mathematical domains rather than treated as a separate technical subject. Students can engage in computational modelling while learning statistics, explore algorithmic structure while developing algebraic reasoning, use simulation to investigate geometric properties, and employ data visualisation tools while developing proportional reasoning. Such integration allows CT practices to be learned in contexts where their mathematical significance is apparent, rather than in artificial isolation.

Fourth, teacher education must attend to embodied and situated perspectives on learning. Many teachers continue to operate within implicitly cognitivist frameworks that treat mathematical understanding as a purely internal achievement. Professional development should therefore address embodied cognition, distributed cognition, gesture studies, and technology-mediated learning, not merely as theoretical concepts but as lenses that can transform how teachers observe, interpret, and respond to students' mathematical and computational activity.

Fifth, assessment practices require substantial rethinking. Written symbol-based assessments, designed within a cognitivist framework, are poorly suited to capturing the embodied, collaborative, and tool-mediated dimensions of computational and mathematical reasoning. Performance-based tasks, design activities, collaborative problem-solving, and multimodal representations can provide richer and more valid evidence of the distributed understanding that 4E-informed pedagogy aims to develop.

8. Challenges and Future Directions

The integration proposed in this paper faces genuine intellectual and practical challenges that future research must address.

A first challenge concerns conceptual clarity. Both CT and 4E cognition are contested constructs encompassing multiple theoretical traditions. Inconsistent usage across the literature creates difficulties for empirical research design and for the cumulative development of theory. The field would benefit from more precise conceptual mapping of how specific 4E dimensions relate to specific CT practices, and from empirical research programmes designed to test these connections.

A second challenge is practical. Embodied and technology-rich pedagogies demand flexible classroom environments, substantial teacher expertise, appropriate digital infrastructure, and time for exploratory activity that current curricular pressures often preclude. Scaling such approaches equitably—ensuring that students in under-resourced settings have access to embodied and computational learning environments—is a significant social justice concern that the field must not sidestep.

A third challenge is theoretical. There is a genuine tension between computational metaphors of mind and the embodied critique of such metaphors. Classical cognitive science modelled the mind as a computer; 4E cognition has contested precisely this model. Future work must clarify how CT can be reconceptualised within embodied and enactive frameworks without simply reasserting the computational assumptions that 4E cognition calls into question. This is not merely a terminological issue but a substantive question about the nature of mathematical reasoning.

Empirically, longitudinal research is needed to examine how embodied computational learning experiences influence mathematical development over time, and whether early embodied engagement with CT concepts produces more durable and transferable understanding than symbol-first approaches. Research should also attend to cultural and contextual variation: because embedded cognition emphasises situated activity, CT practices and their embodied expressions are likely to vary across educational contexts, languages, and communities in ways that universalising frameworks risk obscuring.

The rapidly expanding role of artificial intelligence in educational contexts represents a further frontier. As AI systems increasingly participate in mathematical problem-solving and learning, extended cognition frameworks will need to be developed and refined to capture the new forms of distributed reasoning that emerge. This is not a distant prospect but an immediate challenge for mathematics education research.

9. Conclusion

This paper has argued that computational thinking and 4E cognition represent complementary developments whose integration can enrich both theory and practice in mathematics education. CT has expanded educational understandings of problem-solving, abstraction, modeling, and algorithmic reasoning; 4E cognition has challenged the internalist and individualist assumptions that have long constrained educational theory by demonstrating that thinking is constitutively embodied, situated, enacted, and extended.

From a 4E perspective, computational reasoning does not occur solely inside the mind. It emerges through dynamic interactions among body, environment, tools, representations, and social participation. Gestures, movement, manipulatives, digital technologies, and collaborative activity are not peripheral supports for mathematical cognition but integral dimensions of it. Recognising this changes what we look for when we study computational and mathematical reasoning, what we value when we assess it, and what we provide when we design learning environments.

A 4E perspective on CT also broadens the meaning of computational thinking beyond coding. CT becomes a situated and embodied practice characterised by interaction, design, exploration, and distributed sense-making. This conception aligns with the most ambitious goals of contemporary mathematics education: developing learners who can reason flexibly and creatively across representational systems, engage productively with uncertainty and complexity, and participate in mathematical culture as genuinely agentic thinkers.

Realising this vision will require sustained theoretical work, carefully designed empirical research, and serious engagement with the practical challenges of implementation. But the stakes are high. In technologically mediated societies where computational and mathematical reasoning are increasingly consequential for participation and agency, mathematics education cannot afford theoretical frameworks that account for only part of what learning involves.

References

1. Abrahamson, D. (2014). Building educational activities for understanding: An elaboration on the embodied-design framework and its epistemic grounds. International Journal of Child-Computer Interaction, 2(1), 1–16. https://doi.org/10.1016/j.ijcci.2014.07.002
2. Abrahamson, D., & Lindgren, R. (2014). Embodiment and embodied design. In R. K. Sawyer (Ed.), The Cambridge handbook of the learning sciences (2nd ed., pp. 358–376). Cambridge University Press.
3. Alibali, M. W., & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: Evidence from learners' and teachers' gestures. Journal of the Learning Sciences, 21(2), 247–286. https://doi.org/10.1080/10508406.2011.611446
4. Brennan, K., & Resnick, M. (2012, April). New frameworks for studying and assessing the development of computational thinking. Paper presented at the Annual Meeting of the American Educational Research Association, Vancouver, Canada.
5. Clark, A., & Chalmers, D. (1998). The extended mind. Analysis, 58(1), 7–19. https://doi.org/10.1093/analys/58.1.7
6. Fofang, J. B., Weintrop, D., Moon, P., & Williams-Pierce, C. (2021). Computational bodies: Grounding computational thinking practices in embodied gesture. In Proceedings of the 15th International Conference of the Learning Sciences (ICLS 2021) (pp. 171–178). International Society of the Learning Sciences.
7. Goldin-Meadow, S. (2014). How gesture works to change our minds. Trends in Neuroscience and Education, 3(1), 4–6. https://doi.org/10.1016/j.tine.2014.01.002
8. Gordon, R., & Ramani, G. B. (2021). Integrating embodied cognition and information processing: A combined model of the role of gesture in children's mathematical environments. Frontiers in Psychology, 12, Article 650286. https://doi.org/10.3389/fpsyg.2021.650286
9. Grover, S., & Pea, R. (2013). Computational thinking in K–12: A review of the state of the field. Educational Researcher, 42(1), 38–43. https://doi.org/10.3102/0013189X12463051
10. Hoyles, C., & Noss, R. (2003). What can digital technologies take from and bring to research in mathematics education? In A. J. Bishop, M. A. Clements, C. Keitel, J. Kilpatrick, & F. K. S. Leung

(Eds.), Second international handbook of mathematics education (pp. 323–349). Kluwer Academic Publishers.

11. Hutchins, E. (1995). Cognition in the wild. MIT Press.
12. Kwon, K., Brush, T. A., Kim, K., & Seo, M. (2025). Embodied learning for computational thinking in a mixed-reality context. Journal of Educational Computing Research. Advance online publication. https://doi.org/10.1177/07356331241291173
13. Lakoff, G., & Núñez, R. E. (2000). Where mathematics comes from: How the embodied mind brings mathematics into being. Basic Books.
14. Newen, A., De Bruin, L., & Gallagher, S. (Eds.). (2018). The Oxford handbook of 4E cognition. Oxford University Press.
15. Papert, S. (1980). Mindstorms: Children, computers, and powerful ideas. Basic Books.
16. Varela, F. J., Thompson, E., & Rosch, E. (1991). The embodied mind: Cognitive science and human experience. MIT Press.
17. Way, J. (2024). Embodied learning in early mathematics education. Education Sciences, 14(7), 696. https://doi.org/10.3390/educsci14070696
18. Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining computational thinking for mathematics and science classrooms. Journal of Science Education and Technology, 25(1), 127–147. https://doi.org/10.1007/s10956-015-9581-5
19. Wilson, M. (2002). Six views of embodied cognition. Psychonomic Bulletin & Review, 9(4), 625–636. https://doi.org/10.3758/BF03196322
20. Wing, J. M. (2006). Computational thinking. Communications of the ACM, 49(3), 33–35. https://doi.org/10.1145/1118178.1118215
21. Yeung, G. W.-L., Ng, O.-L., & Zhang, Y. (2024). Young children's embodied computational thinking developed with touchscreen mathematics applications. Quadrante, 33(2), 11–35. https://doi.org/10.48489/quadrante.37071