Advancing research and practice in integrating computational thinking in mathematics education

Avanços da investigação e da prática na integração do pensamento computacional na educação matemática

Oi-Lam Ng
The Chinese University of Hong Kong
Hong Kong SAR
oilamn@cuhk.edu.hk

José Antonio González-Calero
Universidad de Castilla - La Mancha
Spain
jose.gonzalezcalero@uclm.es

Hélia Jacinto
UIDEF, Instituto de Educação, Universidade de Lisboa
Portugal
hjacinto@ie.ulisboa.pt

Introduction

Currently, there is a broad consensus that computational thinking (CT) constitutes an essential skill that must be developed in students from an early age (Bers et al., 2022; Resnick, 2006; Zhang et al., 2023). The relevance of CT stems from its capacity to equip students with attitudes and skills for navigating an increasingly digitized world, where problem-solving processes, algorithmic literacy, and data fluency are significant (Shute et al., 2017; Weintrop et al., 2016; Wing, 2011). The core root of CT dates to the prominent work of Seymour Papert (1980), who put forward an educational approach to CT, in that learning occurs during activities that encourage construction of tangible or digital artifacts, which become "objects-to-think-with" for constructing cognitive structures in the process. This approach was later popularized by Wing's (2011) conceptual definition, CT is "the thought processes involved in formulating problems and their solutions, so that the solutions are represented in a form that can be effectively carried out by an information-processing agent" (p. 20).

https://doi.org/10.48489/quadrante.39744

In mathematics education, CT has drawn attention as a foundational skill for developing mathematical literacy and equipping learners with essential problem-solving competence (OECD, 2020, 2023). As such, educational curricula worldwide, including in Portugal, have begun to embrace CT as a fundamental component, recognizing its potential in cultivating not only computational skills, but also fostering synergistic learning of mathematics. The integration of CT into mathematics curricula represents a recognition of how computer science and mathematical communities share common conceptual underpinnings and practices (Ng et al., 2023). At the same time, there are important implications about how educators and researchers may rethink what it means to teach and learn mathematics in computational contexts. For example, this integration contributes to educational opportunities for applying mathematical knowledge to construct or anticipate CT artefacts and advancing new mathematical knowledge in parallel with CT development through different forms of interplay between CT and mathematics (Ye et al., 2023). Despite research advancements made in the last decade showing evidence of the educational benefits of this relationship, there still exists a significant need for further research in the integration of CT in mathematics education; realizing the potential of this integration requires addressing theoretical gaps while fostering innovation in design and pedagogy.

Frameworks and perspectives for the interplay between CT and mathematics

One area in need of future research in the field lies in developing conceptual frameworks and understanding for the interplay between CT and mathematics. Though current literature shows no consensual definition or model of CT, recent researchers have made significant progress in conceptualising how CT and mathematical practices intersect in educational contexts. Weintrop et al. (2016), have conceptualized a taxonomy of computational practices in mathematical and scientific endeavours, as comprised of data practices, modelling and simulation practices, computational problem-solving practices, and systems thinking practices, which are demonstrated in conjunction to achieve specific scientific and mathematical goals. Barcelos and Silveira (2014) summarized three high-order skills that may be “exchanged” between CT and mathematics, namely alternating between different semiotic representations; establishing relationships and identifying patterns; and building descriptive and representative models. In their Delphi study, Kallia et al. (2021) captured the collective opinion of 25 mathematics and computer science experts regarding the opportunities for addressing CT in mathematics education, highlighting three important aspects: problem solving, the cognitive processes involved in problem-solving, and the transposition of solutions in such a way that it can be transferred or outsourced to another person or a machine. This concurs with Baldwin et al. (2013) who posited: “the general reasoning and problem-solving skills characteristic of computer science are powerfully effective and closely interwoven with those of mathematics” (p. 77).

Overall, there is extensive research demonstrating that CT serves as a bridge between mathematical thinking and computer science practices, highlighting their shared elements, such as abstraction, problem decomposition, and pattern recognition (Benton et al., 2016; Pei et al., 2018; Yadav et al., 2014). Conversely, the work of Cui and Ng (2021) is one of few investigating the potential challenges students experience in CT-based mathematics environments. These challenges were conceptualized and analysed from the perspective of synergies and differences between CT and mathematical thinking, which considers both procedural and conceptual challenges. Thus, there is a need to further examine the difference between computational and mathematical concepts as understood by students learning to program.

In this Special Issue, the following articles make contribution to the research by underscoring the interplay between CT and mathematics, while framing the integration of CT in mathematics education from diverse perspectives. Yeung and Ng (2024) focus on the CT competence young children demonstrated in a touchscreen application, drawing upon embodied cognition as a lens for understanding how CT may be expressed by children verbally and with their hand actions on the touchscreen. Their study contributes toward understanding the incorporation of embodied actions in learning and communicating computer science concepts as a form of embodied CT. It also draws attention on how CT can be supported in non-traditional programming environments for young children, by focusing on children’s verbal and non-verbal actions with touchscreen applications in a problem-solving context.

Sánchez-López et al. (2024) present a study on the impact of using floor robots as educational tools to enhance CT and mental rotation skills among second and third graders, recognizing that mental rotation is an important spatial reasoning skills necessary for comprehending and learning geometrical concepts. Their intervention incorporating Beebots has proven to be highly effective in enhancing both CT and mental rotation skills among the students. This study underscores the potential benefits of integrating computational and spatial reasoning activities into early education curricula.

Barbosa and Maltempi (2024) explore the interplay between reflective thinking and computational thinking within Constructionist Educational Computational Experiences that focus on programming with Scratch. Using a Design-Based Research methodology, the authors facilitated these experiences to a group of children attending a Non-Governmental Organization in Brazil. Through the analysis of “learning stories” and leveraging Dewey's and Papert's educational theories, the study highlights how reflective and computational thinking reciprocally enhance the learning process. Specifically, the article identifies a distinct thinking style termed “computational reflective thinking”, which plays a crucial role in developing mathematical meanings and solving problems encountered during the programming projects.

Silva and Javaroni (2024) examine the relationship between CT and the formation of mathematical concepts from the Vygotskian perspective of the Cultural and Historical Theory, considering that human mental development is related to evolutionary and historical perspectives, mediated by cultural tools. From this, they analysed a trio of students carrying out tasks related to regular polygons using Scratch and GeoGebra software. This investigation generates new understandings about the formation of mathematical concepts as a sequence of action formation in the material plane (through decomposition and pattern recognition), external language plane (through algorithms), and mental plane (through abstraction).

Grizioti et al. (2024) address the question: what does mathematics education have to gain from the integration of CT in its curricula? They suggest that this integration should focus on engaging in mathematical thinking using programming as a means of expressing mathematical ideas, rather than as an end to itself. Their empirical study explores secondary students using MaLT2, an online 3D Turtle Geometry modeler, to generate computational solutions to math problems. Through an investigation of how CT can support mathematization, their study offers insights into the intersection of CT and mathematical reasoning. The results showed that CT practices could be used in different ways for solving the same problem computationally, and depending on the approach, they could promote either mathematical meaning-making or computer science meaning-making.

Bayer et al. (2024) investigate the link between CT and mathematical modelling in secondary mathematics education. They conducted a four-day mathematical modelling project with 14 students from grades 9 to 11 in Germany. Targeting the CT components demonstrated during the project, they identified data collection, pattern recognition, and abstraction as emerged in students' modelling activities. They highlight the nature of modelling problems as offering rich opportunities to develop CT skills. Hence, their study illustrates the synergy between CT and mathematical modelling as a fruitful avenue for integrating CT into mathematics education in today’s digital era.

Innovation for practice in integration of CT in mathematics education

Another line of empirical researchers has examined diverse aspects of the practice of CT-mathematics integration, shedding light on the role of programming tools, task designs, and instructional approaches on learning outcomes for CT and mathematics. For instance, specific task designs, such as Scratch-based activities, have been shown to promote both CT concepts (e.g., loops, variables) and CT practices (e.g., debugging, modelling) in mathematical contexts (Rodríguez-Martínez et al., 2020; Shumway et al., 2021). There is a long tradition of using computational tools for supporting mathematics thinking and learning. Ye et al. (2023) classified the array of educational computing into screen-based programming (e.g., MATLAB, Arduino, Scratch, Sketchpad) and tangible programming (e.g. KIBO robot 18 Kit; Bee-Bot robot; GGBot, Botley). Besides, CT is not only an essential skill addressed in conventional programming activities; unplugged activities can offer young children's CT development even without the use of any programming tools (del Olmo-Muñoz et al., 2020; Sung et al., 2017). Thus, exploring how tools interact with teachers and students' mathematical cognition is both a necessary and intriguing topic.

Besides innovating new tools and learning environments, the methodological design of fostering CT in mathematics teaching and learning, and vice versa, remains an important area for investigation. This includes examining teaching practices in supporting the conceptual, social, and affective aspects of CT-based mathematics learning to shed light on how CT supports concretizing abstract mathematical ideas, and how CT-based activities can offer a cognitively engaging, collaborative, and equitable environment for mathematics learning. In this regard, the following articles in this Special Issue illustrates a vision for improving the practice of integrating CT into mathematics education.

Ligeiro et al. (2024) examine the integration of CT and geometric reasoning in 7th-grade through a teaching experiment on the topic of Operations with figures. The results highlight that a deliberate combination of CT and geometry not only facilitates knowledge development in both domains but also allows for their integration in a cyclical and iterative way. The study further identifies and discusses challenges such as difficulties in connecting CT and geometric reasoning, students' familiarity with programming tools, and the intricacies of geometric reasoning processes. The paper concludes that while the integration of CT and geometric reasoning is both feasible and beneficial, it requires flexible teaching strategies that consider students' cognitive development and include an inquiry-based approach.

Mateus et al. (2024) situates the integration of CT in the study of affine function through a teaching experiment conducted in an eighth-grade classroom. The targeted CT practices were abstraction, decomposition, pattern recognition, analysis and definition of algorithms, and development of habits for debugging and optimizing processes. Functional thinking analysis focused on: the function representations, contextual and symbolic generalization, and mathematical modelling. The results show that CT practices and dimensions of functional thinking were integrated during students' task resolution, highlighting the important role of the task context and the different types of representation facilitated by Scratch in supporting students' transition from concrete examples to more general situations.

Barreiros and Brunheira (2024) designed CT activities in the form of open-ended problems with the use of spreadsheet with 5th and 6th grade students. An action-research was undertaken, with results showing that the spreadsheet serves as a tool to developing CT as well as student learning of algebraic symbolism. For example, it mobilized CT practices, especially in algorithmics, pattern recognition, and debugging. Moreover, students acquired understanding of algebraic expressions, establishing connections between the symbolic language of the spreadsheet and algebraic symbolism. They highlight the interaction between the teacher and the students as significantly contributed to these results.

Ribera Puchades et al. (2024) explored CT through unplugged activities with the board game, Colour Code, which address various CT and visualization skills in the game. As a curricular enrichment program, 16 students participated in the designed game-based learning activity, with results indicating that the participants effectively apply CT skills, such as decomposing the problem, being iterative, and error debugging. Additionally, they employed advanced visualization skills such as visual differentiation and analyzing figure-ground relationships to solve the challenges. The research highlights the innovation of board games as effective teaching and learning tools in the geometry classroom, allowing for the development of CT and visualization skills.

Challenges and opportunities for developing computational thinking in tertiary and teacher education

The journey towards seamless integration of CT into mathematics classrooms is filled with challenges that primarily stem from varied levels of teachers' understanding and their ability to effectively incorporate CT principles into educational practices. Teachers often struggle to connect CT with mathematical content, largely due to a lack of empirical support and practical examples that illustrate the integration of CT into mathematics teaching (Broley et al., 2024; Kaup, 2022). Additionally, teachers' insufficient knowledge about CT can lead to its relegation to plain programming activities, rather than its integration as a fundamental component of mathematical problem-solving (Nordby et al., 2022).

The design and implementation of mathematics teacher education programs that effectively incorporate CT is a complex issue. It requires a well-structured approach that encompasses both initial teacher education and ongoing professional development. These programs must equip both pre-service and in-service teachers with the necessary skills and knowledge to effectively integrate CT into their mathematics instruction (Chan et al., 2021). Promising research results highlight how professional development sessions focused on CT practices—such as abstraction, debugging, and decomposition—can help teachers raise the cognitive demand of mathematics tasks (Rich et al., 2024).

This Special Issue comprises four manuscripts that collectively explore the challenges and opportunities associated with developing CT within tertiary education and mathematics teacher education programs. In the context of preservice mathematics teacher education, the study by Almeida and Seki (2024) examines the possibilities of relating computational thinking with mathematical modelling, whether in solving real world problems, or in the analysis and exploration of available mathematical models to describe real phenomena. Their research aims to know how mathematical modelling promotes computational thinking, by drawing on theoretical foundations of CT and mathematical modelling. The empirical work is distributed across two different scenarios, one of them involving 3rd year undergraduate students in a subject on ordinary differential equations, and the other with 4th year undergraduate students in a subject on mathematical modelling for mathematics education. In one of the scenarios, in which students solved a problem about the growth of a city's car fleet, computational thinking was identified as a thought process involved in formulating and solving problems, that is a tool for problem-solving. In the other scenario, in which students modelled the speed of a parachutist from jump to landing, computational thinking emerged as a means of analysing mathematical models of real situations, where computer simulation played a decisive role.

Nogueira et al. (2024) investigated how a board game in an unplugged setting could develop CT among early childhood and elementary students. Conducting qualitative-interpretative analysis on data from experiments with teachers in a master's continuing education course, the study found that the game effectively promoted CT skills like algorithm exploration and problem-solving. It also served as an interdisciplinary tool that extended beyond mathematical content. However, issues with the game's rules were noted, leading to collaborative recommendations for material improvements. The research underscores the value of playful unplugged activities in fostering student engagement and autonomy in learning.

Branco and Barros' (2024) study concerns the challenges for future teachers in working with Scratch in elementary schools. They explored the challenges by focusing on integrating geometry, measurement, and CT in a professional development context. Four master's students preparing to teach elementary education participated in the study and engaged with the task "The class garden". Results reveal that future teachers identified opportunities to link mathematical knowledge, such as calculating the perimeter and area of rectangles, with CT practices. They also anticipate challenges, including class management and addressing student difficulties. The study highlights how Scratch fosters connections between CT and mathematics learning while offering practical insights for future classroom applications.

Acosta et al. (2024) contextualised the integration of CT in mathematics education in early childhood education. They presented and analysed three tasks that promote the link between computational and algebraic thinking through repetition patterns. Fifty-one pre-service early childhood teachers from Spain were surveyed about their knowledge and beliefs about the link between computational and algebraic thinking through repetition patterns within the given tasks. The data suggest that the teachers exhibited confusion between components, strategies and soft skills of CT, that CT is mainly linked to number sense and algebraic thinking. Further, they advise the design of tasks to take a multidisciplinary perspective to improve the CT-mathematics integration in early childhood education.

Final remarks

In summary, for further contributing to the research and practice of this important field of CT-mathematics integration, this Special Issue probes into the current state of research, which has taken up a variety of perspectives to understand how computational and mathematical practices converge. At the same time, this Special Issue includes empirical studies exploring methodological design to inform on how tools, pedagogy, tasks, assessment, as well as teacher education and professional development can contribute to developing the field. The integration of CT into mathematics education represents a promising opportunity to enrich students' problem-solving capabilities and prepare them for a technologically driven future. This special issue aims to contribute to this area by showcasing cutting-edge research and practical insights that advance our understanding and application of CT in mathematics education. With research effort, the possibilities and future of educating students to be prepared for the demands of the 21st century can be realized by considering a productive CT-mathematics integration from early years education.

References

Acosta, Y., Pincheira, N., & Alsina, Á. (2024). Estableciendo vínculos entre el pensamiento computacional y el pensamiento algebraico en educación infantil: Implicaciones para la práctica docente. *Quadrante*, *33*(2), 338–362. https://doi.org/10.48489/quadrante.36181

Almeida, L., & Seki, J. (2024). Modelagem matemática como meio de integração do pensamento computacional na educação matemática. *Quadrante*, *33*(2), 267–291. https://doi.org/10.48489/quadrante.36900

Baldwin, D., Walker, H. M., & Henderson, P. B. (2013). The roles of mathematics in computer science. *ACM Inroads, 4*(4), 74–80. https://doi.org/10.1145/2537753.2537777

Barbosa, L., & Maltempi, M. (2024). Construção do conceito de Pensamento Reflexivo Computacional em Experiências Computacionais Educativas Construcionistas. *Quadrante*, *33*(2), 58–81. https://doi.org/10.48489/quadrante.36899

Barcelos, T. S., & Silveira, I. F. (2014). Computational Thinking and Mathematics: possible relationships revealed by an analysis of national curriculum guidelines. In V. Wang (Ed). *Handbook of research on education and technology in a changing society* (pp. 922–934). IGI Global.

Barreiros, M., & Brunheira, L. (2024). Práticas de pensamento computacional e desenvolvimento do sentido de símbolo: Uma experiência no 2.º ciclo com a folha de cálculo. *Quadrante*, *33*(2), 223–243. https://doi.org/10.48489/quadrante.36208

Bayer, L., Bracke, M., Lantau, J. M & Theobald, M. (2024). Exploring aspects of computational thinking in mathematical modelling projects: Insights from a project week in a German secondary school. *Quadrante*, *33*(2), 130–150. https://doi.org/10.48489/quadrante.36870

Benton, L., Hoyles, C., Kalas, I., & Noss, R. (2017). Bridging primary programming and mathematics: Some findings of design research in England. *Digital Experiences in Mathematics Education, 3*, 115–138. https://doi.org/10.1007/s40751-017-0028-x

Bers, M. U., Strawhacker, A., & Sullivan, A. (2022). *The state of the field of computational thinking in early childhood education.* OECD. https://dx.doi.org/10.1787/3354387a-en

Branco, N., & Barros, P. M. (2024). Contributos sobre o pensamento computacional na formação inicial de professores: Uma experiência com o Scratch para o 1.º Ciclo. *Quadrante*, *33*(2), 315–337. https://doi.org/10.48489/quadrante.36983

Broley, L., Buteau, C., Modeste, S., Rafalska, M., & Stephens, M. (2024). Computational thinking and mathematics. In B. Pepin, G. Gueudet, & J. Choppin, (Eds.), *Handbook of Digital Resources in Mathematics Education*, (pp. 323–360). Springer. https://doi.org/10.1007/978-3-031-45667-1_12

Chan, S. W., Looi, C. K., Mahedirata, S., & Kim, M. S. (2021). A systematic review of teachers' preparedness towards computational thinking integration in mathematics. In C. K. Looi, B. Wadhwa, V. Dagiené, P. Seow, Y. H. Kee, & L. K. Wu (Eds.), *Proceedings of the 5th APSCE International Computational Thinking and STEM in Education Conference* (pp. 153–155). Asia-Pacific Society for Computers in Education.

Cui, Z., & Ng, O. L. (2021). The interplay between mathematical and computational thinking in primary school students' mathematical problem-solving within a programming environment. *Journal of Educational Computing Research, 59*(5), 988–1012. https://doi.org/10.1177/0735633120979930

del Olmo-Muñoz, J., Cózar-Gutiérrez, R., & González-Calero, J. A. (2020). Computational thinking through unplugged activities in early years of Primary Education. *Computers & Education, 150*, 103832. https://doi.org/10.1016/j.compedu.2020.103832

Grizioti, M., Kynigos, C., & Milrad, M. (2024). Computational thinking in the service of mathematics education: The case of animating programmable 3D models in MaLT2. *Quadrante*, *33*(2), 110–129. https://doi.org/10.48489/quadrante.37379

Kallia, M., Van Borkulo, S. P., Drijvers, P., Barendsen, E., & Tolboom, J. (2021). Characterising computational thinking in mathematics education: A literature-informed Delphi study. *Research in Mathematics Education, 23*(2), 159–187. https://doi.org/10.1080/14794802.2020.1852104

Kaup, C. F. (2022). Mapping the relations between computational thinking and mathematics in terms of problem-solving. *Acta Didactica Norden*, *16*(4), 9185. https://doi.org/10.5617/adno.9185

Ligeiro, C., Jacinto, H., & Piedade, J. (2024). Desenvolvimento do pensamento computacional e do raciocínio geométrico no 7.º ano: Resultados de uma experiência de ensino. *Quadrante*, *33*(2), 151–192. https://doi.org/10.48489/quadrante.37328

Mateus, A., Oliveira, H., & Piedade, J. (2024). A task for integrating computational thinking in the learning of affine function: an exploratory study with 8th grade students. *Quadrante*, *33*(2), 193–222. https://doi.org/10.48489/quadrante.37041

Ng, O. L., Leung, A., & Ye, H. (2023). Exploring computational thinking as a boundary object between mathematics and computer programming for STEM teaching and learning. *ZDM Mathematics Education, 55*(7), 1315–1329. https://doi.org/10.1007/s11858-023-01509-z

Nogueira, M., Rostirola. S., Siple, I., Cecatti, M., & Munhoz, R. (2024). Explorando o pensamento computacional em um jogo de tabuleiro: A "Patrulha Canina"como ambiente de aprendizagem desplugada. *Quadrante*, *33*(2), 292–314. https://doi.org/10.48489/quadrante.36156

Nordby, S. K., Bjerke, A. H., & Mifsud, L. (2022). Primary mathematics teachers' understanding of computational thinking. *KI-Künstliche Intelligenz*, *36*, 35–46. https://doi.org/10.1007/s13218-021-00750-6

OECD (2019). *PISA 2018 Assessment and Analytical Framework.* OECD Publishing. https://doi.org/10.1787/b25efab8-en

OECD (2023). *PISA 2022 Mathematics Framework. PISA 2022 Assessment and Analytical Framework*. OECD Publishing. https://doi.org/10.1787/7ea9ee19-en.

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

Pei, C. (Yu), Weintrop, D., & Wilensky, U. (2018). Cultivating Computational Thinking Practices and Mathematical Habits of Mind in Lattice Land. *Mathematical Thinking and Learning, 20*(1), 75–89. https://doi.org/10.1080/10986065.2018.1403543

Resnick, M. (2006). Computer as paintbrush: Technology, play, and the creative society. *Play = Learning*, 192–206. https://doi.org/10.1093/acprof:oso/9780195304381.003.0010

Ribera Puchades, J. M., Rotger García, L., & Petro Balaguer, A. B. (2024). Desarrollo de habilidades de pensamiento computacional y visualización a través del juego de mesa Colour Code. *Quadrante*, *33*(2), 244–266. https://doi.org/10.48489/quadrante.36881

Rich, K. M., Yadav, A., & Fessler, C. J. (2024). Computational thinking practices as tools for creating high cognitive demand mathematics instruction. *Journal of Mathematics Teacher Education*, *27*(2), 235-255. https://doi.org/10.1007/s10857-022-09562-3

Rodríguez-Martínez, J. A., González-Calero, J. A., & Sáez-López, J. M. (2020). Computational thinking and mathematics using Scratch: An experiment with sixth-grade students. *Interactive Learning Environments, 28*(3), 316–327. https://doi.org/10.1080/10494820.2019.1612448

Sánchez-López, M., Gonzalez-Calero Somoza, J. A. & del Olmo-Muñoz, J. (2024). Exploring the role of floor robots in enhancing computational thinking skills and mental rotation in second and third graders. *Quadrante*, *33*(2), 36–57. https://doi.org/10.48489/quadrante.36860

Shumway, J. F., Welch, L. E., Kozlowski, J. S., Clarke-Midura, J., & Lee, V. R. (2023). Kindergarten students' mathematics knowledge at work: The mathematics for programming robot toys. *Mathematical Thinking and Learning, 25*(4), 380–408. https://doi.org/10.1080/10986065.2021.1982666

Shute, V. J., Sun, C., & Asbell-Clarke, J. (2017). Demystifying computational thinking. *Educational Research Review, 22*, 142–158. https://doi.org/10.1016/j.edurev.2017.09.003

Silva, E. C. & Javaroni, S. L. (2024). The possible relationships between the development of computational thinking and the formation of mental actions of students in mathematics classes. *Quadrante*, *33*(2), 82–109. https://doi.org/10.48489/quadrante.36198

Sung, W., Ahn, J., & Black, J. B. (2017). Introducing computational thinking to young learners: Practicing computational perspectives through embodiment in mathematics education. *Technology, Knowledge and Learning, 22*(3), 443–463. https://doi.org/10.1007/s10758-017-9328-x

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

Wing, J. M. (2011). Research Notebook: Computational Thinking—What and Why? *The Link - Magazine of the Carnegie Mellon University School of Computer Science*, *6*, 20-23.

Yadav, A., Mayfield, C., Zhou, N., Hambrusch, S. E., & Korb, J. T. (2014). Computational thinking in elementary and secondary teacher education. *ACM Transactions on Computing Education, 14*(1), 1–16. https://doi.org/10.1145/2576872

Ye, H., Liang, B., Ng, O. L., & Chai, C. S. (2023). Integration of computational thinking in K-12 mathematics education: A systematic review on CT-based mathematics instruction and student learning. *International Journal of STEM Education, 10*(3). https://doi.org/10.1186/s40594-023-00396-w

Yeung, G., Ng, O.-L., & Zhang, Y. (2024). Young children's embodied computational thinking with touchscreen mathematics applications. *Quadrante*, *33*(2), 11–35. https://doi.org/10.48489/quadrante.37071

Zhang, Y., Ng, O.-L., & Leung, S. (2023). Researching Computational Thinking in Early Childhood STE(A)M Education Context: A Descriptive Review on the State of Research and Future Directions. *Journal for STEM Education Research, 6*(3), 427–455. https://doi.org/10.1007/s41979-023-00097-7