UC Merced
Proceedings of the Annual Meeting of the Cognitive Science Society

Title

From "A Bridge Too Far" to Infrastructural Integration: Designing Computational Thinking for Early Childhood

Permalink

https://escholarship.org/uc/item/4fb0n6p0

Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 48(0)

Authors

Sanchez-Costa, Thaiz Priscilla
Gonzalez-Perilli, Fernando
Abelda—o, Romina
et al.

Publication Date

2026

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at https://creativecommons.org/licenses/by/4.0/

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

From "A Bridge Too Far" to Infrastructural Integration: Designing Computational Thinking for Early Childhood

Thaiz Priscilla Sánchez-Costa (thaizsanchez@gmail.com)[1,2], Fernando Gonzalez Perili[2], Romina Abeldaño[2], Joaquín Márquez[2], Emilia Casaravilla[2], Marcos Gimenez[2], Alar Urruticoechea[3] & Ana Cristina Pires[4]

[1]Centro Interdisciplinario en Cognición para la Enseñanza y el Aprendizaje, Udelar

[2]Facultad de Información y Comunicación, Udelar, Uruguay

[3]Universidad Católica del Uruguay

[4]Instituto Universitário de Lisboa, ISCTE, Portugal

[5]Universidade de Lisboa, ITI-LARSyS, Portugal

Abstract

Computational thinking (CT) in early childhood is increasingly understood as a set of foundational problem-solving practices rather than as early programming. Yet, a persistent challenge remains: how cognitively informed designs can be integrated into everyday classroom practice. This challenge echoes the longstanding "bridge" problem in cognitive science and education, concerning the difficulty of aligning cognitive principles with pedagogical routines and institutional conditions. In this paper, we examine this integration problem through a hybrid tangible-digital CT learning design developed through a participatory design process and implemented in public preschool classrooms with children aged 4-6 years. Focusing on sequencing, decomposition, and debugging, we analyze how embodied interaction and peer collaboration support anticipatory reasoning, error-based revision, and shared regulation during problem solving. Preliminary qualitative results indicate that children construct and revise procedural plans through tangible action, engage in collaborative debugging, and sustain attention in rule-based tasks. Crucially, these outcomes depend not only on cognitively plausible tasks, but on their infrastructuring into classroom orchestration and existing pedagogical routines. We argue that participatory design provides a concrete mechanism for addressing the bridge problem by enabling multi-level integration of cognitive theory, interaction design, and educational practice.

Keywords: computational thinking; early childhood education; tangible interaction; participatory design; infrastructuring; multi-level integration; classroom orchestration

Introduction

The relationship between cognitive science and educational practice has long been marked by both promise and difficulty. In his influential essay *A Bridge Too Far*, Bruer Bruer (1997)argued that attempts to derive direct prescriptions for classroom practice from neuroscience were misguided, given the gap between levels of explanation. Rather than a direct bridge, he proposed cognitive psychology as an intermediate level capable of mediating between neural mechanisms and education. This argument crystallized a broader challenge that remains central to cognitive science: how to integrate processes that unfold at different organizational levels, timescales, and forms of practice.

Subsequent work has both reinforced and reframed Bruer's caution. Horvath and Donoghue revisited the "bridge too far" argument, showing that the core problem is not simply a lack of neuroscientific evidence, but the incommensurability between organizational levels: what emerges at the level of neural processes cannot be directly prescribed at the level of pedagogy or educational policy (Horvath & Donoghue, 2016). More recently, other scholars have suggested moving beyond the bridge metaphor altogether, arguing that neuroscience and education should not be conceived as separated by a gap to be crossed, but as a common field to be cultivated through sustained interdisciplinary collaboration (Basso & Cottini, 2023). Together, these perspectives shift the problem from one of translation to one of integration across levels.

Recent work within Cognitive Science has begun to address this integration challenge more directly by questioning the traditional separation between basic research and applied contexts. Chan, Nagashima, and Closser (2023) argue that participatory design (PD) can advance cognitive science itself by embedding theoretical commitments within authentic sociotechnical settings, allowing cognitive theories to be developed, tested, and refined through sustained engagement with real-world practices. From this perspective, PD is not merely a methodological choice to address the integration problem by aligning cognitive science with real learning.

This integration problem becomes particularly visible in educational technology. Despite decades of theoretically informed innovation, many educational technologies fail to achieve sustained classroom adoption (Facer & Selwyn, 2021). This phenomenon—often described as the *last mile problem*—reflects a recurrent misalignment between cognitively plausible designs and the pedagogical routines, institutional constraints, and sociotechnical infrastructures of real classrooms. Tools may demonstrate strong cognitive affordances in experimental or pilot settings, yet falter when confronted with everyday practices of orchestration, shared material use, curricular pacing, and teacher mediation. The difficulty, therefore, is not merely technical but structural: it concerns how insights at the cognitive level can be made operative within educational systems.

Early childhood education brings this problem into sharp relief. At this level, learning is deeply grounded in embodied action, social interaction, and play, while classrooms are shaped by tightly structured routines, limited resources, and heterogeneous groups of learners. When new technologies are introduced in this context, their success depends not only on

In G. Boleda, I. Dautriche, M. Maldonado, C. Saldana and T. Torrent (Eds.), *Proceedings of the 48th Annual Conference of the Cognitive Science Society* ©2026 the author(s). This work is licensed under a Creative Commons Attribution 4.0 International License (CC BY).

whether they support learning mechanisms such as attention, engagement, or feedback, but on whether they can be integrated into existing pedagogical practices and institutional ecologies. Many promising designs succeed at the level of interaction but fail to stabilize as classroom practices, leading to abandonment after initial trials.

In this paper, we argue that such failures can be understood as instances of the broader integration problem articulated by Bruer and subsequent authors Bruer (1997); Horvath and Donoghue (2016). Rather than treating this problem as a gap to be crossed through stronger prescriptions or more refined cognitive principles, we approach it as a design challenge: how to align cognitive theory, pedagogical practice, and institutional conditions within real educational settings. To this end, we draw on the notion of *infrastructuring* from PD research, which conceptualizes design as the ongoing work of aligning artifacts, routines, roles, and organizational arrangements over time (Chen, 2024; Karasti et al., 2018). PD, from this perspective, functions as a concrete mechanism through which levels of analysis can be connected and stabilized in practice.

We analyze a hybrid tangible–digital computational thinking (CT) activity for preschool classrooms as an empirical case of integration in practice. By following how theory-informed design decisions are negotiated, adapted, and stabilized through participatory processes, we show how CT emerges not only through artifacts, but through their integration into pedagogical routines and classroom infrastructures.

Our contribution is therefore twofold. First, we provide empirical evidence of how core computational thinking practices—such as sequencing, decomposition, and debugging—can be scaffolded in early childhood through embodied and collaborative activity. Second, and more centrally, we show how PD operates as an infrastructural practice that connects cognitive theory with educational practice across levels of organization. In doing so, we reconceptualize the "bridge too far" problem not as a failure of theory in practice, but as an invitation to study how integration is achieved—or fails to be achieved—within the sociotechnical ecologies of education.

Related Work

This section reviews prior work relevant to the present study along four complementary axes: (i) computational thinking (CT) in early childhood education, (ii) unplugged pedagogies and learning progressions, (iii) tangible and embodied approaches to CT learning, and (iv) collaboration, distributed cognition, and classroom mediation. Rather than revisiting the general motivation for introducing CT in preschool, we focus on empirical and theoretical strands that inform the design and analysis of integrated, classroom-ready learning environments.

Computational thinking in early childhood

In early childhood education, CT refers to foundational problem-solving practices such as decomposition, abstraction, sequencing, problem reformulation, and systematic testing (Shute, Sun, & Asbell-Clarke, 2017). Rather than introducing programming as an end in itself, preschool CT activities typically enact these practices through play, narrative, and guided exploration aligned with children's developmental capacities.

Preschool children can engage in CT-related practices when tasks are appropriately structured (Bers, Strawhacker, & Sullivan, 2022; Efrosyni-Alkisti, Christos-Apostolos, Zygouris, & Bagos, 2025). Yet, outcomes depend on design, instructional support, and assessment approaches. Many initiatives remain isolated from everyday classroom routines (Liu et al., 2024). Less is known about how CT can be sustained through coherent learning progressions aligned with pedagogical and institutional constraints.

Unplugged pedagogies and learning progressions

Unplugged approaches reduce technological barriers and ground early CT concepts in bodily and social activity (Bers, 2020; Huang & Looi, 2021). Projects such as Scratch Tactile similarly translate block-based programming into physical manipulation and tabletop interaction (Scratch Tactile Project, n.d.). Critical reviews of unplugged pedagogies in K–12 computer science and CT education report positive effects on engagement, accessibility, and conceptual understanding, particularly for younger learners (Choiriyah, Pertiwi, Rohanah, & Valencia, 2025; Huang & Looi, 2021). Although unplugged activities are frequently implemented as stand-alone experiences, with limited articulation to subsequent digital or programming-based tasks, and with insufficient attention to progression across activities and lessons (Huang & Looi, 2021).

Unplugged activities are often designed and evaluated in isolation, rather than as components of broader learning cycles that unfold over time (Huang & Looi, 2021; Liu et al., 2024). Their role in linking embodied, tangible, and digital forms of CT therefore remains underexplored.

In early childhood classrooms, new activities must fit structured routines, shared materials, and limited time, space, and device access (Liu et al., 2024). This makes clear progressions linking unplugged and digital tasks are therefore essential for sustainable adoption.

Tangible and embodied approaches to CT learning

Tangible user interfaces (TUIs) and embodied interaction support early CT by grounding reasoning in physical action. They align with young children's motor development and embodied cognition, helping reduce representational demands in abstract tasks (Antle, 2013; Arévalo, Baldo, González-Perilli, & Ibáñez, 2015; Marshall, 2007; Pires et al., 2019). By coupling physical manipulation with digital feedback, tangible systems make procedural relations and action–outcome mappings more visible (Price & Falcão, 2009).

Tangible and embodied CT approaches support sequencing, debugging, and decomposition while reducing reliance on screens Pires et al. (2023); Rocha, Gonçalves, Pires, Nicolau, and Guerreiro (2025). Tangible and embodied CT approaches support sequencing, debugging, and decomposition while reducing reliance on screens

Collaboration, distributed cognition, and classroom mediation

CT learning is socially mediated. Collaborative activities support shared problem solving, sequential reasoning, pattern recognition, and strategy verbalization (Berland & Wilensky, 2015; Bers et al., 2022). Tangible environments make actions visible and negotiable, allowing reasoning to emerge through coordination among learners, artifacts, and classroom routines, consistent with distributed cognition accounts of thinking as organized across people, artifacts, and situated practices (Choiriyah et al., 2025; Horn, Solovey, Crouser, & Jacob, 2009; Hutchins, 1995).

Collaborative learning depends on co-regulation across cognitive, social, and material dimensions (Järvelä, Gašević, Seppänen, Pechenizkiy, & Kirschner, 2020). In early CT, tangible and embodied activities can support guided participation and shared regulation (Noordin, 2025), but these benefits rely on teacher mediation of turn-taking, materials, and emotional regulation.

Teacher orchestration and classroom infrastructure are often treated as background factors, despite being central to CT integration. Successful adoption depends on teachers' practices, support structures, and alignment with classroom routines (Liu et al., 2024).

Positioning of the present work

This study examines how a hybrid tangible–digital CT activity supports early CT practices in preschool classrooms. It extends prior work by focusing not only on the artifact, but on how embodied action, peer collaboration, teacher mediation, and classroom conditions shape its integration into a coherent learning progression.

Objectives

This study examines how cognitively informed CT designs can be integrated into early childhood classroom practice through four objectives:

1. To design a gamified, tangible CT activity for children aged 4–6 that supports foundational problem-solving practices and bridges toward block-based programming.
2. To develop unplugged and embodied activities as preparatory stages in a coherent CT learning progression.
3. To implement and iteratively refine a functional prototype compatible with Android tablets, offline use, and shared-device in public preschool classrooms.
4. To investigate a participatory co-design process with a public educational technology agency to identify material, pedagogical, and infrastructural conditions for classroom orchestration and scalable adoption.

Methodology

The study was conducted across five public early childhood classrooms intentionally selected to capture variation in institutional conditions, classroom size, and teachers' prior CT experience. Participants were mainly 5–6-year-old children, with some 4-year-olds in inter-level groups. Although all teachers had completed national CT training, their confidence and classroom technology use varied, enabling analysis of pedagogical appropriation beyond technical access.

The intervention used a tangible user interface (TUI) (Marichal et al., 2017) through which children built simple programs by arranging physical command blocks, linked to a tablet application that provided immediate visual feedback (see Figure 1). Inspired in part by Scratch Tactile (Scratch Tactile Project, n.d.), the design combined unplugged tabletop activities and tangible-digital interaction as preparation for later block-based programming, emphasizing embodied sequencing and collaborative planning.

Data Sources

Data collection combined video-recorded observations, field notes, teacher interviews, and reflective workshops to triangulate interactional, pedagogical, and design-oriented perspectives. Observations of unplugged and plugged CT activities captured teacher orchestration, peer collaboration, engagement, and breakdowns in sequencing, orientation, or rule interpretation. Interviews and teacher workshops documented prior CT experience, classroom constraints, pedagogical expectations, and evolving perceptions of feasibility and challenges. Workshops with regional CT facilitators added insights into adoption dynamics and support structures.

Together, these sources supported a multi-level analysis of classroom interaction, teacher-mediated adaptation, and infrastructural conditions for integration.

Implementation Phases and Iterations

The intervention followed a three-phase process combining classroom enactment, observation, and iterative redesign.

Phase 1: Contextual inquiry and early trials. We conducted two visits to each of five public preschool classrooms to examine pedagogical routines and gather prototype feedback. Each visit included an unplugged bodily sequencing activity and a preliminary tangible-digital session. These 90-minute sessions allowed us to observe children's task comprehension, teacher scaffolding, and practical challenges such as device sharing, spatial constraints, turn-taking, and tactile input issues.

Phase 2: Iterative refinement and learning cycle structuring. Findings from Phase 1 informed refinements to both interface design and activity sequencing. We worked with two cohorts:

- **Intensive Cohort:** Three groups from two schools participated in three-session cycles combining unplugged physical activities, tangible tabletop interaction, and the updated digital prototype.

- **Single-Session Cohort:** Two institutions (including both level 4 and level 5 classrooms) participated in a single 90-minute session using the revised app.

Both cohorts showed comparable levels of engagement and task success, suggesting the robustness of the design and learning flow. The longer intervention allowed richer documentation of how children and educators adapted to the CT dynamics.

Phase 3: Synthesis and consolidation. Insights from both implementations informed the consolidation of a replicable learning cycle. Emphasis was placed on robustness across real-world constraints—such as shared-device use, varying levels of teacher experience, and limited instructional time—rather than on optimizing specific learning outcomes. The result is a design framework oriented toward ecological validity and scalable classroom adoption.

Intervention Structure

Each session consisted of two phases: 1. Unplugged activity (30 min) - Materials: grid maps + tangible pieces (arrows, flag) - Goal: construct sequences to move a character

2. Plugged activity (30–40 min) - Tablet-based application - Same logic but with automated feedback

Children worked in groups of 2–3 with adult facilitation.

Ethical Considerations

The study protocol was approved by the authors' institutional Research Ethics Committee, and school implementation was authorized by the national public education authority. Children participated voluntarily after written parental or guardian consent; teachers also provided informed consent. Children without signed consent could take part in the activities but were not audiovisually recorded. All data were anonymized and handled according to applicable ethical guidelines.

Data Analysis

We conducted a qualitative thematic analysis.

Steps: 1. Familiarization with video and field notes 2. Initial coding (e.g., collaboration, debugging, sequencing) 3. Grouping into categories 4. Identification of emergent themes

Preliminary Results

Preliminary findings are organized around three dimensions: (i) emergent computational thinking (CT) practices, (ii) collaborative participation and shared regulation, and (iii) pedagogical implications at the classroom level.

Design constraints and the effects of iteration

The iteration revealed how the design of the tangible materials shaped the participation of the children. Early versions caused orientation and manipulation difficulties, as ambiguous alignment, flexibility, size, and interlocking mechanism affected directionality and the construction of stable sequences.

Iterative refinements to materials, visual cues, group size, and activity sequencing reduced difficulties, increased autonomy, and supported more sustained engagement. These findings show that learning outcomes depended on the alignment of task design, materials, participation formats, and classroom conditions.

Emergent computational thinking practices

Across both unplugged and tangible–digital activities, children exhibited early forms of core CT practices through tangible interaction. These included the development of basic sequencing, task decomposition, and error correction strategies. Children frequently constructed ordered action plans using physical elements and adjusted these plans in response to outcomes, indicating an emerging understanding of procedural structure.

Notably, children demonstrated the ability to anticipate the logical consequences of instruction sequences prior to execution. This anticipatory reasoning suggests the formation of internal predictive models rather than purely reactive behavior. When discrepancies arose between expected and observed outcomes, children engage in spontaneous trial-and-error strategies, incrementally constructing solutions treating errors as informative signals. This form of embodied debugging was often enacted through bodily repositioning, rearrangement of tangible elements, and incremental modification of action sequences. In several groups, children used gestures to anticipate trajectories before selecting materials, tracing paths in the air or on the table to indicate intended movements. In other cases, planning emerged through direct interaction with tangible materials, where children tested partial sequences and adjusted them dynamically as they progressed.

Collaborative debugging and shared regulation

Tangible interaction fostered collaborative forms of problem solving and cognitive regulation among peers. Children frequently co-constructed plans, negotiated sequence order, and jointly identified errors during task execution. These interactions were characterized by early metacognitive verbalizations (e.g., "you made a mistake there," "better two steps forward"), which functioned as shared control signals guiding collective revision of strategies. Furthermore, debugging emerged as a central practice. When a program failed, children engaged in error detection and correction through discussion, gesture, and manipulation of tangible materials. In some cases, children removed or replaced specific pieces; in others, they reoriented entire sequences. Collaboration appeared to distribute cognitive demands across participants, with children adopting complementary roles such as monitoring goal achievement, counting steps, or manipulating physical components. Sustained attention was observed more consistently in contexts where children were actively engaged in constructing and testing rule-based sequences with tangible materials, compared to moments of waiting or limited interaction within the same activity.

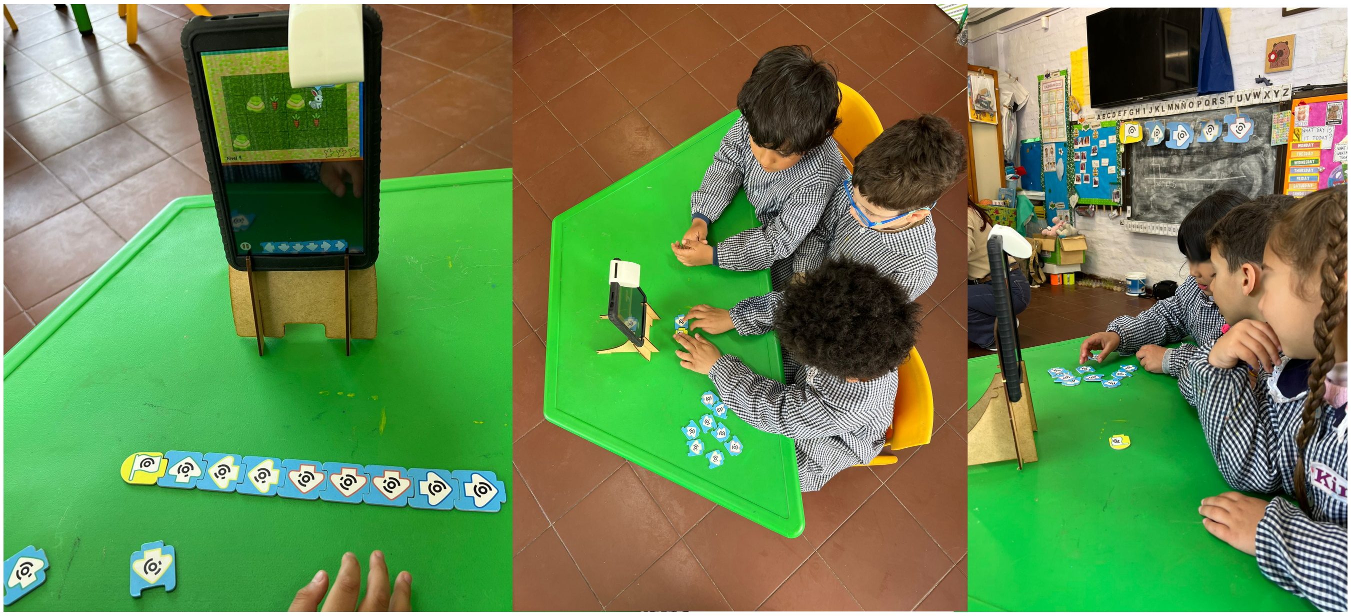

Figure 1: Interactions with computational thinking through tangible programming: Three classroom perspectives. **Left:** Children arranged the command blocks in sequence in front of a tablet-based system. **Center:** Illustration of collaborative interaction in a small group of children as they construct a program using tangible pieces around a shared device. **Right:** Representation of game dynamics in program construction, highlighting how children negotiate, revise, and take turns while collaboratively developing their program.

However, collaboration was not always stable. In early implementations, groups often fragmented, with children constructing individual programs instead of coordinating a shared solution. Conflicts over material control and differing interpretations of directionality also disrupted joint activity. In contrast, later implementations showed more sustained collaboration, including turn-taking, shared construction of sequences, and even cross-group interactions where children sought or provided help.

These findings suggest that collaborative debugging is not only a cognitive process but also a socially organized activity that depends on the stability of group interaction and the availability of shared representations.

Pedagogical implications at the classroom level

Facilitation of the teacher's role Teacher and adult mediation played a central role in shaping children's engagement, regulating participation, and sustaining task-oriented behavior. Differences in mediation strategies were associated with significant variation in group dynamics and learning opportunities. For example, adult prompts such as asking where the character should go next or how to interpret a direction helped externalize reasoning and align group understanding. In contrast, in contexts with limited or intermittent mediation, children were more likely to disengage, shift to exploratory or unrelated play, or work individually rather than collaboratively. Periods of waiting without guidance were also associated with increased motor restlessness and reduced focus.

From a pedagogical perspective, the tangible CT activities seamlessly integrated with existing classroom routines, including station-based rotations and the use of shared physical materials. Teachers reported that the system enabled children to engage autonomously in tasks for extended periods, reducing the need for constant adult supervision and allowing educators to focus on orchestration and targeted scaffolding.

Teacher perceptions of the proposal Teachers expressed positive evaluations of the proposed learning sequence, particularly highlighting unplugged embodied activities as effective preparatory stages for subsequent digital interaction. The approach was perceived as compatible with pedagogical frameworks centered on play, narrative, and active learning. Teachers emphasized that tangible and unplugged components supported children's comprehension of rules and sequences before introducing on-screen representations, thereby easing the transition to digital environments.

Discussion

The present study contributes to the cognitive science of learning by examining how CT practices can emerge in early childhood through a carefully designed integration of tangible interaction, collaborative activity, and classroom infrastructure. Rather than treating learning outcomes as the direct consequence of exposure to a technological artifact, our findings highlight the importance of aligning cognitive mechanisms, interactional affordances, and pedagogical environments.

CT as predictive and error-driven activity in early childhood

The observed anticipatory reasoning and embodied debugging behaviors suggest that preschool children engage with CT tasks by constructing and revising internal predictive models. Children did not merely react to outcomes after execution; instead, they often reasoned about expected consequences before acting, and treated errors as informative signals that guided subsequent revisions. This pattern is consistent with cognitive accounts that frame learning as an iterative process of prediction, feedback, and adjustment, rather than as linear skill acquisition (Järvelä et al., 2020; Yang, Su, & Li, 2024).

Importantly, these processes were supported by tangible interaction, which externalized procedural structure and reduced representational demands. By making sequences and transformations physically manipulable, the design enabled children to reason about procedures in ways that are compatible with their developmental stage, supporting early forms of abstraction without requiring symbolic notation.

Collaboration as distributed cognitive regulation

Collaboration played a central role in shaping CT practices. The visibility and shareability of tangible actions supported peer-based co-regulation, where planning, monitoring, and error detection were distributed across children, artifacts, and verbal exchanges. Early metacognitive utterances functioned as coordination signals that guided collective problem solving and sustained engagement. From a cognitive perspective, these interactions can be understood as instances of distributed cognition, in which reasoning is not localized within individual learners but emerges through coordinated activity. In line with Horn et al. (2009), the findings suggest that collaborative tangible environments can reduce individual representational demands while enriching the quality of reasoning by enabling shared access to intermediate states and decision points.

Reframing the bridge problem as infrastructural integration

The results speak to a broader theoretical issue in cognitive science and education: the persistent difficulty of translating cognitively informed designs into effective classroom practices. Following critiques of direct prescriptive "bridges" between cognitive theory and instruction (Bruer, 1997; Horvath & Donoghue, 2016), our findings support the view that the critical work of integration occurs at intermediate levels of organization. In our case, the success of the intervention depended not only on cognitively plausible tasks, but also on their embedding within existing classroom infrastructures, including routines, spatial arrangements, time constraints, and shared-device dynamics.

Participatory design functioned here as a mechanism of *infrastructuring*, enabling the alignment of theoretical assumptions, interaction design, and pedagogical practice over time (Chen, 2024; Karasti et al., 2018). Iterative collaboration with teachers allowed tacit constraints and opportunities to surface, stabilizing learning cycles that were robust across varying institutional conditions. In line with recent arguments within cognitive science, this suggests that participatory design can operate not merely as a methodological choice, but as a means of advancing theory by situating cognitive principles within real sociotechnical systems (Chan et al., 2023). The comparable engagement and task success observed in both intensive and single-session implementations further indicate that prior infrastructural work can reduce reliance on prolonged exposure, shifting emphasis from dosage to design coherence.

Implications for the design of early CT learning environments

Taken together, the findings underscore the importance of designing early CT learning environments as coupled cognitive–social–material systems. Effective designs should (i) support anticipatory reasoning and informative error feedback, (ii) make procedural structure externally visible and open to negotiation, and (iii) explicitly account for classroom orchestration as a design parameter rather than as an implementation afterthought. From this perspective, cognitively informed interaction design must be complemented by participatory processes that align learning activities with pedagogical routines and institutional conditions. These considerations extend beyond any specific technological artifact and point toward a more general framework for theory-informed educational design in early childhood.

Conclusion

This study examined how computational thinking practices emerge in preschool classrooms through a hybrid tangible–digital learning design embedded in everyday educational contexts. The results indicate that young children can engage in core CT practices—such as sequencing, decomposition, and debugging—by constructing predictive action plans, responding to informative errors, and collaboratively regulating problem-solving activity. Crucially, the findings show that cognitively informed design alone is insufficient to ensure effective classroom enactment. Instead, successful CT learning depends on the integration of cognitive principles with interactional affordances and classroom infrastructures, including routines, material arrangements, and teacher orchestration. In this sense, our results extend the classical "bridge problem" by showing that integration across levels of organization is not achieved through direct prescription, but through infrastructural alignment in practice.

We argue that participatory design provides a productive mechanism for this alignment. By engaging teachers and institutional stakeholders as co-designers, participatory processes can surface contextual constraints, stabilize learning cycles, and support sustainable appropriation of CT activities. Taken together, these findings contribute to a cognitively grounded yet practice-sensitive account of computational thinking in early childhood education, highlighting infrastructuring as a key challenge and opportunity for future research.

Acknowledgments

The authors used ChatGPT, a large language model, to support language editing, organization of ideas, and iterative refinement of text during manuscript preparation. All theoretical framing, methodological decisions, data analysis, interpretation of results, and final content remain the sole responsibility of the authors.

References

Antle, A. N. (2013). Exploring how children use their hands to think: An embodied interactional analysis. *Behaviour & Information Technology*, *32*(9), 938–954.

Arévalo, A., Baldo, J., González-Perilli, F., & Ibáñez, A. (2015). *What can we make of theories of embodiment and the role of the human mirror neuron system?* (Vol. 9). Frontiers Media SA.

Basso, D., & Cottini, M. (2023). Cognitive neuroscience and education: Not a gap to be bridged but a common field to be cultivated. *Sustainability*, *15*(2), 1628.

Berland, M., & Wilensky, U. (2015). Comparing virtual and physical robotics environments for supporting complex systems and computational thinking. *Journal of science education and technology*, *24*(5), 628–647.

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

Bers, M. U., Strawhacker, A., & Sullivan, A. (2022). The state of the field of computational thinking in early childhood education.

Bruer, J. T. (1997). Education and the brain: A bridge too far. *Educational Researcher*, *26*(8), 4–16.

Chan, J. Y.-C., Nagashima, T., & Closser, A. H. (2023). Participatory design for cognitive science: Examples from the learning sciences and human- computer interaction. *Cognitive Science*, *47*(10), e13365.

Chen, B. (2024). A framework for infrastructuring sustainable innovations in education. *Journal of the Learning Sciences*, *33*(3), 583–612.

Choiriyah, C., Pertiwi, L., Rohanah, R., & Valencia, E. (2025). Teacher's perspectives on young children's computational thinking skills through unplugged coding activities, a case study of children aged 5-6 years. *Indonesian Journal of Early Childhood Education Studies*, *14*(1), 54–68.

Efrosyni-Alkisti, P.-K., Christos-Apostolos, M., Zygouris, N. C., & Bagos, P. G. (2025). Computational thinking in primary and pre-school children: A systematic review of the literature. *Education Sciences*, *15*(8), 985.

Facer, K., & Selwyn, N. (2021). Digital technology and the futures of education: Towards 'non-stupid'optimism. *Futures of Education initiative, UNESCO*.

Horn, M. S., Solovey, E. T., Crouser, R. J., & Jacob, R. J. (2009). Comparing the use of tangible and graphical programming languages for informal science education. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 975–984).

Horvath, J. C., & Donoghue, G. M. (2016). A bridge too far–revisited: reframing bruer's neuroeducation argument for modern science of learning practitioners. *Frontiers in psychology*, *7*, 377.

Huang, W., & Looi, C.-K. (2021). A critical review of literature on "unplugged" pedagogies in k-12 computer science and computational thinking education. *Computer Science Education*, *31*(1), 83–111.

Hutchins, E. (1995). *Cognition in the wild*. MIT press.

Järvelä, S., Gašević, D., Seppänen, T., Pechenizkiy, M., & Kirschner, P. A. (2020). Bridging learning sciences, machine learning and affective computing for understanding cognition and affect in collaborative learning. *British Journal of Educational Technology*, *51*(6), 2391–2406.

Karasti, H., Botero, A., Parmiggiani, E., Baker, K., Marttila, S., Saad-Sulonen, J., & Geirbo, H. C. (2018). Infrastructuring in pd: what does infrastructuring look like? when does it look like that? In *Proceedings of the 15th participatory design conference: Short papers, situated actions, workshops and tutorial-volume 2* (pp. 1–3).

Liu, Z., Gearty, Z., Richard, E., Orrill, C. H., Kayumova, S., & Balasubramanian, R. (2024). Bringing computational thinking into classrooms: A systematic review on supporting teachers in integrating computational thinking into k-12 classrooms. *International Journal of STEM Education*, *11*(1), 51.

Marichal, S., Rosales, A., Sansone, G., Pires, A. C., Bakala, E., Perilli, F. G., & Blat, J. (2017). Ceta: open, affordable and portable mixed-reality environment for low-cost tablets. In *Proceedings of the 19th international conference on human-computer interaction with mobile devices and services* (pp. 1–7).

Marshall, P. (2007). Do tangible interfaces enhance learning? In *Proceedings of the 1st international conference on tangible and embedded interaction* (pp. 163–170).

Noordin, N. H. (2025). Computational thinking through scaffolded game development activities: A study with graphical programming. *European Journal of Educational Research*, *14*(4), 1137–1149.

Pires, A. C., Abreu, L. V., Rocha, F., Simão, H., Guerreiro, J. a., Nicolau, H., & Guerreiro, T. (2023). Tactopi: Exploring play with an inclusive multisensory environment for children with mixed-visual abilities. In *Proceedings of the 22nd annual acm interaction design and children conference* (p. 411–422). New York, NY, USA: Association for Computing Machinery. Retrieved from https://doi.org/10.1145/3585088.3589389 doi: 10.1145/3585088.3589389

Pires, A. C., González Perilli, F., Bakała, E., Fleisher, B., Sansone, G., & Marichal, S. (2019). Building blocks of mathematical learning: Virtual and tangible manipulatives lead to different strategies in number composition.

In *Frontiers in education* (Vol. 4, p. 81).
Price, S., & Falcão, T. P. (2009). Designing for physical-digital correspondence in tangible learning environments. In *Proceedings of the 8th international conference on interaction design and children* (pp. 194–197).
Rocha, F., Gonçalves, D., Pires, A. C., Nicolau, H., & Guerreiro, T. (2025, May). Exploring collaboration in programming activities with children with visual impairments: a 10-session study in a school setting. *Proc. ACM Hum.-Comput. Interact.*, *9*(2). Retrieved from https://doi.org/10.1145/3710971 doi: 10.1145/3710971
Scratch Tactile Project. (n.d.). *Scratch tactile.* Retrieved from https://www.scratchtactile.org/ (Accessed: May 6, 2026)
Shute, V. J., Sun, C., & Asbell-Clarke, J. (2017). Demystifying computational thinking. *Educational research review*, *22*, 142–158.
Yang, W., Su, J., & Li, H. (2024). Demystifying early childhood computational thinking: An umbrella review to upgrade the field. *Future in Educational Research*, *2*(4), 458–477.