ATHEnA: Designing a Cognitive-Informed Toolkit for Computational Thinking Education

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Abstract

In a digitally driven society, thinking computationally can be a crucial transversal competency for successfully navigating the 21st century. Despite the recognized pedagogical and cognitive value of *computational thinking* (CT), its effective integration into current curricula remains fragmented and often misaligned with the actual needs of learners and educators. This position paper presents *ATHEnA*, a research project aimed at designing a theoretical framework and implementation for integrated CT education able to strategically merge the dimensions of cognition, pedagogy, and education. Building on findings from experimental and qualitative studies exploring the interplay between CT, executive functions, and educational outcomes, ATHEnA introduces an early-stage digital intervention: a suite of mini-games specifically designed to support the development of both CT and core cognitive processes, aiming to ensure accessibility, inclusivity, and scalability in CT education. This proposal represents a comprehensive approach to preparing students for the challenges and opportunities of the digital age, fostering critical thinking, creativity, and adaptability in an evolving technological landscape, while actively innovating the traditional curriculum.

Keywords

Computational Thinking, Educational Technology, Cognitive Training, Game-based Learning

1. Introduction

In 21-st-century, technology-rich education, there is an growing demand for transversal skills that can address emerging and complex challenges. In this context, computer science (CS) is not only essential but also calls for a paradigm shift in educational practices. Too often reduced to the instrumental use of digital tools, CS is, in fact, the science of information processing–a foundational competence for understanding and shaping the world we live in [1]. Compared to the skills taught in more traditional curricula, information processing is highly multifaceted–both in terms of its structure (cognitive and other underpinnings) and its functions (implementation and application, with or without digital devices)–making it particularly complex to manage within educational settings.

Within this framework, the concept of *computational thinking* (CT) is introduced–not as the act of programming or using a computer, but as the cognitive process that underlies it. Defined as the developer's mental process [2], CT involves reformulating a problem and structuring a solution in such a way that a third agent–typically a machine–can carry it out effectively to produce the correct outcome [1]. Training this skill can yield multiple benefits, as it essentially represents an advanced form of problem solving that can be applied across different subjects and real-world situations.

Despite its potential and the growing body of scientific research, the integration of CS and CT into education remains limited and fragmented. This is due to several factors. First, unlike more established disciplines such as math, CS education is still relatively young and lacks consolidated methodologies. Second, there is a pressing need for effective strategies that enable the seamless integration and scalability of CS/CT within existing curricula. Third, teachers are not adequately trained in these areas.

The educational field, aware of these challenges, is actively seeking new and impactful approaches. However, many of the current proposals remain isolated from the broader curriculum and fail to achieve

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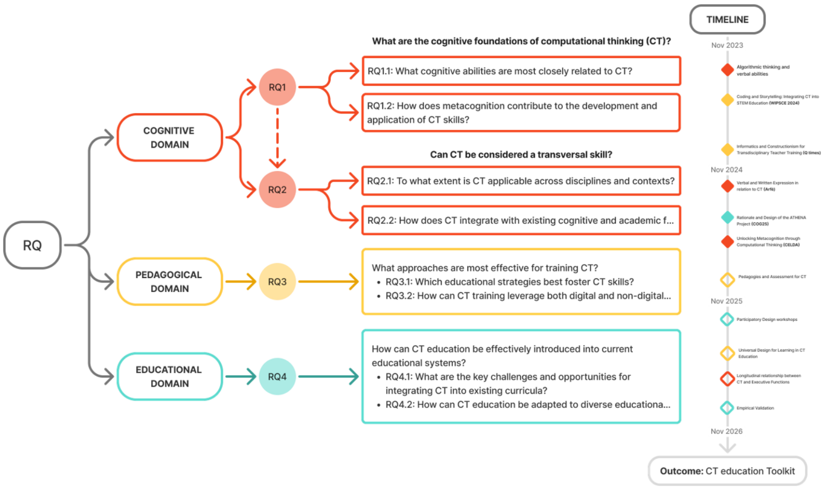

Figure 1: Research questions and project timeline overview.

their intended goals [3]. Addressing issues of effective integration and scalability is therefore a top priority and calls for continued effort and innovation.

2. Research Framework and Objectives

Coding, educational robotics, and other CT-related practices are increasingly spreading in K–12 education. However, their introduction often remains scattered, resulting in limited impact and a generally superficial approach. In most cases, these activities are implemented as short-term trends in isolated sessions, rather than being organically integrated into the curriculum with a long-term perspective.

In the presented educational scenario, the main research question guiding this project has been: *"What are the key transversal skills that future learners need to successfully navigate the challenges of the 21st century, and what role do CS and CT play in this context?"*

In addition, a gap in the existing literature lies in the disciplinary separation of CT research, which hinders the development of educational interventions that are both pedagogically grounded, technically sound, and cognitively informed. For this reason, as illustrated in Figure 1, the main research question has been unpacked to address three interconnected dimensions: cognitive, pedagogical, and educational.

- *Cognitive domain*: What are the cognitive underpinnings of CT? How is metacognition involved?
- *Pedagogical domain*: Can CT be considered a transversal skill, and how should it be taught?
- *Educational domain*: How can CT be meaningfully introduced within current curricula?

The research's goal is then developing and validating a theoretical framework connecting these three domains. In this regard, the project ATHENA represents a concrete implementation of the mentioned framework and a tangible output of this PhD journey. The project ATHENA combined with a toolkit of educational resources aims to integrate the aforementioned dimensions while more broadly fostering positive attitudes toward IT, developing IT competencies, and promoting IT literacy.

3. Theoretical Background

The theoretical framework underpinning this project is multidisciplinary, drawing from cognitive science, pedagogy, computer science education, and human-centered design. It emphasizes constructionist teaching methodologies that foster personal and affective engagement with technological content, positioning computer science as an interdisciplinary space for learning. The framework is further grounded in cognitive science research on the foundations of higher-order thinking skills, while also addressing the socio-cultural dimensions of educational change [4].

3.1. Computational Thinking, Cognitive Underpinnings and Existing Tools

CT includes five main components: abstraction, problem decomposition, identifying and correcting errors (debugging), recognizing patterns in data, and expressing problem solutions as sequences of actions [2]. CT has demonstrated significant pedagogical value, with notable impacts on both key skills and cognitive functions [5, 6]. Empirical studies have shown that CS/CT interventions can enhance essential cognitive abilities such as problem solving, reasoning, logical thinking, and executive functions [3]. Moreover, strong connections have been found between CS/CT and metacognitive processes, as well as with other higher-order thinking skills (HOTS) [4].

The transferability and generalization of such skills are highly relevant, as they empower learners to better approach and manage both complexity and ambiguity [6]. In this regard, existing CT education resources often focus on programming-based tasks or open-ended environments like Scratch, which require structured pedagogical approaches and adequate teacher training. Tools, both with and without digital devices–such as Scratch, Bebras, CS Unplugged, and Code.org–tend to emphasize task-solving or creative activities but rarely address the underlying cognitive and metacognitive processes of CS/CT [4, 5]. The novelty of this proposal compared to existing approaches relies in a stronger integration of metacoognitive, executive functions and other learning prerequisites training in CT concepts teaching.

3.2. Constructionism and Transdisciplinary Computer Science Education

Constructionism is an educational theory that posits learning is most effective when individuals actively construct knowledge through hands-on engagement with materials and experiences [7]. Papert emphasized the importance of building artifacts–whether physical objects or computational models–as a way to deepen conceptual understanding. These artifacts provide learners with immediate feedback, supporting reflection, iteration, and the development of critical thinking within meaningful contexts.

Recent research supports this perspective, highlighting the effectiveness of constructionist approaches in both CT and CS education for promoting cognitive and metacognitive development. Arfè et al. [8] showed that introducing constructionist coding activities in primary schools can significantly enhance executive functions and other key foundations for learning and self-regulation. Similarly, constructionist approaches and scaffolded protocols have proven highly effective for learners with special needs, yielding significant benefits in terms of learning outcomes and cognitive empowerment [9].

Rooting CS/CT education in constructionist practices further promotes positive attitudes and affective engagement in learning, while fostering a mindset oriented toward exploration, adaptation, and reflection [7]. As Mishra highlights with respect to constructionist models [10], meaningful learning emerges from the interplay between learner agency and contextualized problem-solving–especially when educational technologies serve as mediators in this process.

Nevertheless, the successful introduction of such approaches is possible only through appropriate teacher training that fosters interdisciplinary thinking, enabling educators to conceptualize CS/CT as a transversal competence that bridges disciplines rather than being confined to technical or vocational learning [11]. Indeed, when approached through a constructionist lens, CS/CT become more than just curricular subjects–they offer opportunities to *learn to learn*, equipping learners to meet the complex demands of today's educational landscape [11].

Within this project, the constructionist framework guides the development of a didactic toolkit for CT education by creating opportunities for learners to actively engage in building computational artifacts, exploring coding projects, and developing simulations. This approach aligns closely with the project's goals, as it promotes deeper conceptual understanding and supports the development of meaningful problem-solving skills in CS and CT.

4. Research Design and Methodology

The project begun in November 2023 by framing the topic with a literature review, involved a set of interconnected studies with mixed methods. The methodology follows three funnels reflecting the three research question's branches:

- *Experimental and quasi-experimental studies* to better define CT cognitive underpinnings through the use of validated tasks and tools with psychometric properties;
- *Qualitative research* involving ethnography, interviews and focus groups aimed at a more comprehensive description of the educational environment and dynamics as well as teachers' perspectives;
- *Participatory design studies* to inform with concrete requirements and hints, the development of tailored solutions, ensuring the relevance and practicality of ATHEnA and further foster a sense of ownership and commitment by the educational community to the implementation of the toolkit. More in detail, workshops conducted in actual school contexts will engage students and teachers as co-designer in processes of design-thinking and human-centered design.

5. Findings to Date and Ongoing Work

Findings to date highlight a promising interplay between CT and key cognitive abilities, particularly problem-solving, verbal reasoning, and metacognition [12]. Literature reviews and empirical studies show that engaging with CT can stimulate strategic reflection, process monitoring, and other core components of metacognitive regulation. Two further studies, one focused on verbal reasoning and creativity, the other on the effects of programming on metacognition, support the potential of CT as a predictor of verbal reasoning and creative performance, as well as a trigger for reflective practices [13].

In parallel, qualitative studies conducted with teachers in primary schools offered valuable insights into the role of CT not only as part of the curriculum but also as a didactic strategy. Nonetheless, they also highlighted several challenges to its effective integration [14]. As reported in several studies, constructionist and interdisciplinary approaches make CT, in educational settings, more than just a subject within informatics; they position it as an inclusive and transversal competence [11]. These findings, even from a broader educational community perspective, emphasize that CS/CT education should not be treated in isolation, but requires the active engagement of both learners and educators within a co-design framework for didactic innovation tailored to real educational needs. Another area of investigation concerns the inclusion and accessibility of CT education for students with special educational needs (SEN). A systematic literature review on this topic highlighted the relevance of educational robotics for this purpose and, more broadly, how CT practices–such as block-based programming–can serve as powerful tools for fostering participation and offering learning opportunities across different subjects [15].

Ongoing work is currently focused on a set of sub-projects. One, now under OSF pre-registration, involves a longitudinal study investigating the relationship between CT and executive functions in primary education. In parallel, data collection is underway on the link between CT and verbal expression within the same target group. Additionally, a systematic literature review and meta-analysis on CT assessment in relation to cognitive functions is being conducted, aiming to define an updated framework of the tools, approaches, and theoretical models used. These findings have laid the groundwork for the development of the ATHEnA project, a serious game designed to support CT education and executive function training, presented in the following section.

5.1. The ATHEnA Project

To address the educational challenge of integrated CT education and training, the ATHEnA project–short for *Algorithmic Thinking, cognitive Enhancement, and Active learning*–was designed. It features a set of minigames embedded in a space adventure narrative designed to help K–12 users develop both CT processes and concepts while simultaneously training executive functions. The game mechanics are grounded in scientific evidence from gamified cognitive training and validated CT activities [16].

Concretely, the toolkit consists of five minigames (Figure 2), each preceded by a brief cognitive activation task. Every challenge takes place on a different planet and can be solved only through the application of CT strategies such as debugging, algorithm design, pattern recognition, and more.

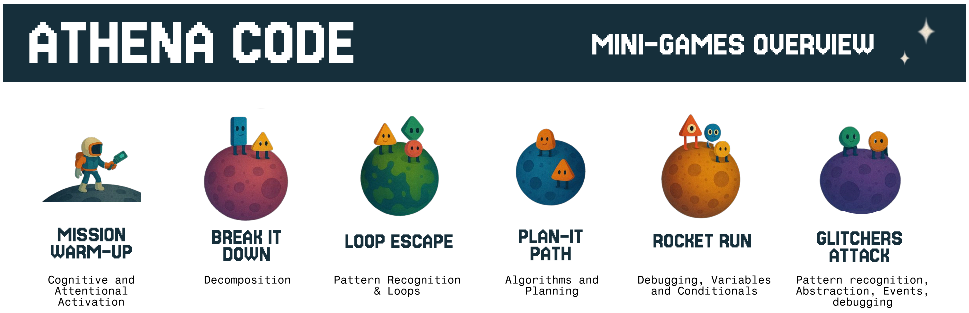

Figure 2: ATHEnA Project minigames overview.

Although each game is standalone, the overarching narrative encourages the progressive exploration of CT concepts and processes through a scaffolded approach. In this way, ATHEnA aims to provide holistic CT training by shifting the focus from code-oriented tasks toward broader cognitive development. The intuitive gameplay and tablet-based format make the game accessible and usable even outside of school settings, supporting autonomous use at home. In parallel with the core mechanics, a feedback system and adaptive difficulty–based on player performance–help sustain engagement by ensuring appropriately challenging tasks.

6. Expected Contribution and Future Work

This research journey is progressively assembling the foundations for a theoretical framework that connects the three domains of cognition, pedagogy, and education. Its goal is to inform the design of a toolkit–comprising both plugged and unplugged components–for integrated CS/CT education. This mapping process seeks to reposition CS/CT not merely as a technical skill, but as a broader learning resource that fosters metacognition, computational problem-solving, and strategic reflection. Informed by both scientific and theoretical evidence through a multidisciplinary lens, the framework also aims to identify sustainable models that address the needs of students and teachers. A concrete example of the framework's possible implementation–and a key contribution of this project–is the ATHEnA initiative, which also addresses inclusion and accessibility for learners with special educational needs. Moreover, this research enriches the existing scientific literature on CT by helping to fill the gap in approaches that consider the interplay between cognitive, pedagogical, and educational dimensions.

Future work will focus on data collection, analysis, and the finalization of ongoing studies, along with a more comprehensive validation of the ATHEnA demo. This will involve a first pilot testing with classrooms of primary students in ecological settings with a quasi-experimental design with pre-post intervention assessment of CT abilities and EFs. Additional refinements and the development of an unplugged version of the game are also planned to support broader and more inclusive dissemination. In parallel, the definition and dissemination of the proposed theoretical framework aim to provide a unified reference for the design of educational activities and teacher training programs.

7. Conclusions

The integration of CT as a transversal skill in education requires a paradigm shift that considers not only technical aspects like coding but also the underlying cognitive processes. This research aims to develop a theoretical framework that explores CT through the lenses of cognition, pedagogy, and education. Initial findings suggest that CT can serve both as a competence and as a tool for learning, particularly in relation to metacognitive strategies. Moreover, qualitative research conducted with teachers and students in school settings highlights the demand for accessible, inclusive, and holistic educational solutions aligned with the needs of real classrooms. Within this framework, the ATHEnA project represents the first step toward implementing this vision, promoting a gamified and narrative-based approach to foster CT and cognitive development. Future work will focus on finalizing the tool and validating it through empirical studies.

Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT-4 for grammar and spelling check. Further, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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