Computational thinking and critical thinking in the context of extended reality–based learning environments

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Abstract: *The article examines how computational thinking and critical thinking address the cognitive demands of extended reality (XR)–based learning environments. Drawing on educational policies and computer science curricula, the study highlights the limitations of traditional approaches centered on abstract algorithmic reasoning when applied to immersive, interactive, and dynamic contexts. Based on a systematic literature review, the paper discusses cognitive processes such as spatial reasoning, embodied interaction, and real–time decision–making that characterize XR learning experiences. The article proposes an integrative perspective in which computational thinking is complemented by the evaluative and reflective mechanisms of critical thinking. The conclusions emphasize the educational significance of this approach for curriculum design, pedagogy, and teacher training, and outline directions for future research on how cognitive processes are reorganized within immersive educational environments.*

Keywords: computational thinking, critical thinking, extended reality, cognitive processes, immersive learning

1. Introduction

The rapid digitalization of educational systems over the past two decades has highlighted the importance of cognitive competencies that enable learners to understand, interact with, and modify the digital world. European educational policy documents and studies coordinated by the Joint Research Centre (JRC), such as the reports *Developing Computational Thinking in Compulsory Education* (Bocconi et al., 2016) and *Reviewing Computational Thinking in Compulsory Education* (Bocconi et al., 2022), define *computational thinking* as a transversal cognitive competence essential for problem formulation, the design of algorithmic solutions, and forms of reasoning that can be implemented in computational systems. These systems are understood as integrated hardware–software assemblages capable of executing algorithms, processing data, and automating problem–solving processes (Bocconi et al., 2016; Bocconi et al., 2022).

At the same time, recent European studies indicate that informatics and computer science have gradually become well–defined subjects within primary and secondary education. The Eurydice report on computer science education in European schools shows that curricula place strong emphasis on core areas such as algorithms, programming, and data processing, confirming the importance of computational thinking for the development of digital competence. However, the same report highlights curricular imbalances, as areas such as modelling and simulation, design and development, and human–system interaction remain underrepresented, despite their growing relevance in contemporary digital environments (Eurydice, 2022).

In parallel, learning environments are undergoing a profound transformation. Beyond the increasingly widespread use of conventional digital technologies in education, extended reality (XR) technologies encompassing virtual, augmented, and mixed reality are being integrated with increasing frequency. These technologies go beyond the mere digitalization of educational content and fundamentally transform how learners interact with knowledge by creating learning experiences based on the overlap and integration of physical and virtual realities.

Although computational thinking provides a relevant framework for understanding algorithmic problem solving and the functioning of digital systems, it does not fully encompass the cognitive processes involved in the effective use of immersive and interactive XR environments. Traditionally, computational thinking emphasizes abstraction, decomposition, and automation, operating predominantly through symbolic manipulation and mediated interaction with technology. In contrast, learning in XR environments involves spatial reasoning, multisensory integration, and the continuous adaptation of actions within a dynamic context in which physical and virtual elements interact permanently in real time.

This divergence between the cognitive characteristics of computational thinking (CT) and the specific nature of XR experiences points to the need for a more detailed analysis of how CT and critical thinking manifest and complement each other in immersive contexts. Rather than introducing a new construct, the article adopts an integrative perspective, examining the limitations of current operationalizations of CT in relation to XR requirements and the role of critical thinking in the evaluation, validation, and justification of decisions in complex digital environments.

Within this framework, the article pursues three main objectives:

(1) a critical evaluation of the role and limitations of *computational thinking* in European education, as defined and implemented in current policies and curricula;

(2) an analysis of the cognitive demands specific to learning in XR environments and the identification of areas in which these demands are insufficiently addressed by current curricular practices (e.g., modelling and simulation, design and development, human–system interaction);

(3) an examination of how *critical thinking* can function as a cognitive regulatory mechanism (evidence evaluation, error detection, decision justification, reflection on consequences) to support the application of computational thinking in XR contexts.

Accordingly, the article seeks to clarify how the evolution of cognitive competencies in digital education can be understood through the interaction between computational thinking and critical thinking in XR contexts, outlining the implications of this interaction for curriculum structuring, learning task design, and methods for assessing cognitive performance.

Critical thinking is viewed as an active process of analysis and reflection through which individuals evaluate information, arguments, and evidence in order to make well–founded decisions (Facione, 2023). It involves examining reasoning processes, identifying errors or informational limitations, comparing available options, and anticipating the consequences of decisions, particularly in complex and uncertain situations. By contrast, computational thinking refers to a structured approach to problem solving based on abstraction, task decomposition, the design of algorithmic solutions, and their verification through testing and debugging, with the potential for implementation in computational systems (Bocconi et al., 2016; Bocconi et al., 2022).

In extended reality environments, these two cognitive frameworks are not mutually exclusive but complementary. Computational thinking supports the organization and modelling of digital interactions, providing the structural foundations for XR systems to function. At the same time, critical thinking plays an essential role in regulation and validation, helping learners to assess the relevance of information, evaluate the quality of system–generated feedback, and justify decisions made in contexts characterized by dynamism, time pressure, and real–time feedback. From this perspective, the use of XR environments underscores the need for the explicit integration of critical thinking into computational thinking–based activities, particularly in tasks involving interpretation, uncertainty management, and the assumption of responsibility for the consequences of actions within an immersive environment.

2. Computational Thinking in European Educational Policies

Over the past decade, computational thinking has assumed a central role in European educational policies, being recognized as a key element for understanding and leveraging information and communication technologies in contemporary educational and social contexts. The increasing emphasis on computational thinking (CT) also reflects a paradigmatic shift in the conceptualization of digital competences: from narrowly defined technical skills associated with operating ICT tools toward cognitive processes focused on problem solving, reasoning, and innovation across all fields of study. Within the context of educational policies, computational thinking is not limited to programming; rather, it represents a mode of thinking that develops problem–solving strategies through the execution, with the support of computers, of solutions constructed through systematic reasoning (Bocconi et al., 2016).

At the European level, debates and policy orientations concerning computational thinking have been significantly shaped by the work of the Joint Research Centre (JRC) of the European Commission. According to the report *Developing Computational Thinking in Compulsory Education* (Bocconi et al., 2016), computational thinking is defined as "a problem–solving methodology that extends the scope of computer science across disciplines, offering a distinctive way of analyzing and developing solutions to problems that can be solved computationally. Through its emphasis on abstraction, automation, and analysis, computational thinking constitutes a core element of the broader field of computer science." The same document states that "computational thinking can be regarded as one of the transversal cognitive competences," alongside literacy and numeracy, which are "fundamental for active participation in contemporary information societies."

Within this conceptual framework, computational thinking is commonly associated with a set of foundational cognitive practices, including abstraction, decomposition, algorithmic thinking, automation, debugging, and generalization. European educational policy documents emphasize that these practices enable learners to analyze complex problems, decompose them into manageable components, and construct structured solutions that can be implemented by humans, computational systems, or a combination of both. From this perspective, programming is highlighted as a means for developing computational thinking rather than an end in itself.

From a curricular standpoint, European countries have adopted diverse approaches to integrating computational thinking into compulsory education. In some education systems, computational thinking is embedded within computer science or informatics subjects across all levels of schooling (primary, lower secondary, and upper secondary), whereas in others it is treated as a transversal competence, less dependent on a specific discipline, and incorporated into mathematics, science, or digital competence frameworks. This diversity of integration approaches is illustrated in Figure 1, which presents the positioning of computational thinking (CT) within curricula based on the results of a survey conducted among ministries of education in various European countries (Bocconi et al., 2016, p. 16).

Table 5. Curriculum location based on the survey of MOEs

Country	Within a subject	Across all subjects	Depends on regional or school curricula
Austria	Informatics (upper secondary level)		
Denmark	Information/technology (in grades 10-12)	(in grades 0-9)	X
Finland	Mathematics (grades 1-9) Crafts (grades 7-9)	Transversal competences (e.g. ICT competences)	X
France	Mathematics (Cycle 2-3, primary level) Math and Technology (Cycle 4- lower secondary)		
Hungary	Information technology (grades 1-4; and grades 9-12)		X
Italy	Informatics/ technology IT Curriculum - Applied Science	X	X
Israel	Computer Science		X
Lithuania	Informatics and Information Technology (IT) (grades 5 -12)		
Malta	ICT subject	Part of Digital Literacy (primary level)	X
Poland	Informatics (grades 0-12)	X	
Portugal	- ICT subject (grades 7-8) - Informatics (grades 10-12)		
Switzerland	X	X (primary and lower secondary level German speaking schools)	
Turkey	ICT and Informatics (grade 5-6)		

Figure 1. Positioning of computational thinking in the compulsory education curriculum (adapted from Bocconi et al., 2016, p. 16).

The observed differences are attributable not only to national educational traditions but also to how the role of computational thinking is conceptualized within the curriculum–sometimes as a distinct subject, and in other cases as a transversal dimension integrated across various areas of study. Beyond these divergent approaches, the report identifies a shared objective at the European level: ensuring that all learners complete compulsory education having developed basic computational thinking competencies.

Although computational thinking has been widely adopted in European educational policies, the report’s authors highlight several significant challenges related to its implementation. These include the lack of a universally accepted definition, uncertainties regarding the curricular positioning of computational thinking, challenges associated with teacher education and professional development, as well as difficulties related to assessment practices. On the one hand, educational policies emphasize the role of computational thinking in fostering analytical and problem–solving abilities. On the other hand, conceptual tensions persist in how it is approached, oscillating between an understanding of computational thinking as a cognitive process and its treatment as curricular content predominantly focused on programming activities.

Moreover, European research in the field of computer science education indicates that the policy–driven emphasis on computational thinking has led to a strong concentration on algorithmic and programming skills, at times to the detriment of other relevant areas of computer science. The Eurydice report on computer science education in Europe highlights that algorithms and programming are addressed at all educational levels, whereas domains such as human–system interaction, design, and development receive considerably less attention (Eurydice, 2022).

From a cognitive perspective, this policy orientation reflects a predominantly symbolic and abstract understanding of digital competence, centered on logical structures, representations, and formal processes. While such an approach is appropriate for traditional digital environments, it proves limited in relation to emerging immersive, interactive, and multisensory learning contexts that characterize innovative educational environments, particularly those integrating emerging technologies such as extended reality, which are increasingly being adopted within European education systems.

In this context, computational thinking can be regarded as an important but insufficient cognitive framework for addressing the demands of contemporary digital education. Although it has been successfully implemented in European policies as a core competence for interacting with the digital world, the transformation of learning environments into experience–centered contexts calls for the development of more comprehensive cognitive frameworks capable of capturing the specific demands of extended reality environments–demands that are not fully addressed by the current, predominantly abstract definition of computational thinking.

3. Computer science education in Europe

The increasing emphasis placed on computational thinking in European educational policies has been accompanied by a significant expansion of computer science education from the early years of schooling. As highlighted in the Eurydice report *Informatics Education at School in Europe*, there is a growing recognition of informatics as an autonomous scientific domain with its own body of knowledge, methods, and ways of thinking, rather than merely a set of operational digital skills.

In this context, the majority of European education systems have integrated informatics either as a distinct subject within the curriculum or as a component of other subjects, most notably mathematics, science, and technology.

To facilitate cross–national comparisons, Eurydice has identified ten core domains of informatics that are commonly reflected in national competence frameworks and curricula: data and information; *algorithms; programming; computing systems; networks; human–system interaction; design and development; modelling and simulation; awareness and empowerment; safety and security*.

This framework provides a coherent and systematic basis for the classification and analysis of learning outcomes associated with informatics competences across

European education systems.

An analysis of this framework reveals that, at all levels of compulsory education, algorithms and programming constitute the most strongly emphasized areas of computer science education, being the most extensively covered domains in the majority of European countries. In many education systems, algorithmic thinking skills and basic programming concepts are introduced as early as primary education and are progressively developed throughout lower and upper secondary schooling.

By contrast, Eurydice data indicate a far more uneven curricular coverage of other informatics domains. For example, *modelling and simulation* are explicitly addressed in only a very limited number of primary–level curricula and remain marginal even at the upper secondary level (Table 1).

Table 1. Representation of the modelling and simulation domain in European computer science curricula

Country	Educational level	Formulation of learning outcomes
Bulgaria	Primary	Explicit learning outcomes related to computational modelling and simulation are specified
Czech Republic	Primary	Introduction of modelling and simulation concepts
	Lower secondary	Consolidation of competences related to the use of models and simulations
	Upper secondary	Application of modelling and simulation to investigate phenomena
Greece	Primary	Use of simulation tools to understand real–world systems and formulate predictions
	Lower secondary / Upper secondary	Progressive development of modelling and simulation competences
France	Primary	Modelling reality using physical, geometric, and digital models
	Lower secondary	Digital simulation of the struct
	Upper secondary	Programming and development of models for physical, economic, and social phenomena
Slovenia	Primary	Explicit learning outcomes related to modelling and simulation
Ireland	Upper secondary	Development of computational models to test scenarios; problem solving through simulation
Netherlands	Upper secondary	Computational modelling of phenomena from other scientific disciplines; use of simulations

The *modelling and simulation* domain remains modestly represented in European curricula, being explicitly included at the primary education level in only five countries (Bulgaria, the Czech Republic, Greece, France, and Slovenia). Among these, only three countries (the Czech Republic, Greece, and France) ensure a coherent and progressive development of this domain across all three educational levels. At the upper secondary level, although modelling and simulation are present in approximately one third of European education systems, they are addressed primarily within interdisciplinary and STEM–oriented contexts. This orientation suggests a fragmented and application–driven integration of the domain rather than a systematic and progressive construction of competences throughout compulsory schooling.

Similarly, design and development, as well as human–system interaction, are among the least frequently addressed themes in European computer science education, despite their high relevance for contemporary digital systems, which increasingly depend on user experience, interaction design, and system modelling. When included, these domains typically appear in optional or specialized computer science courses at the upper secondary level (Table 2).

Table 2. Presence of the design and development and people–system interface domains in European computer science curricula

Domain	Educational level	Countries
Design and Development	All three educational levels	Greece, Poland, Turkey
	Lower and upper secondary	Ireland, France, Latvia
	Upper secondary (predominantly)	More than one third of European education systems
People–system interface	Primary	Greece, Croatia, Hungary
	Lower secondary	Latvia
	Upper secondary	Denmark, Estonia, Sweden

The uneven distribution of learning outcomes suggests that computer science curricula predominantly emphasize abstract, symbolic, and procedural dimensions, while experiential, interactive, and system–centered components remain less developed. From a pedagogical perspective, computer science is thus approached primarily as an algorithmic discipline, in line with the classical view of computational thinking promoted at the European level. Although this approach is appropriate for traditional digital platforms, it is less suited to understanding emerging educational environments based on interaction and immersion.

At the same time, the Eurydice report highlights that curricular progression is not uniform across all domains of computer science. While the number of learning outcomes increases from primary to lower and upper secondary education, this progression is particularly evident in areas such as algorithms, programming, and safety and security. By contrast, domains related to human–computer interaction and design and development do not exhibit a clear developmental trajectory, suggesting a lack of continuity in the formation of these competences throughout schooling. In this context, recent empirical evidence from lower secondary education indicates that the use of visual programming environments enhances students' computational thinking, motivation, and transdisciplinary competences, supporting the role of project–based approaches in addressing curricular gaps (Veverița, 2025).

Comparative studies of primary digital education curricula across Europe show clear differences in how programming, algorithms, and digital skills are taught, pointing to ongoing challenges in ensuring coherent and continuous learning across educational levels (Veverița & Braicov, 2025).

From a cognitive perspective, these curricular gaps point to a deeper issue that extends beyond curriculum design alone. The limited emphasis on modelling, simulation, and human–system interaction suggests a potential misalignment between the current framework of computer science education and the cognitive demands associated with functioning in complex digital environments. As educational technologies increasingly evolve toward the use of extended reality, the development of competences such as spatial reasoning, embodied interaction, and real–time problem solving becomes essential–competences that are insufficiently addressed in current computer science curricula.

Taken together, Eurydice findings indicate that, despite the progress made in integrating computer science and computational thinking into compulsory education across Europe, certain educational and cognitive gaps persist. These gaps are particularly evident in domains directly relevant to extended reality environments. Identifying and addressing them therefore requires a reconsideration of the cognitive frameworks underpinning computer science education. It is within this context that *the analysis of the cognitive demands of extended reality–based learning environments and the need to articulate an expanded perspective on thinking—one that goes beyond the conceptual limits of computational thinking—become especially pertinent.*

4. Cognitive Demands of Extended Reality Environments

The curricular gaps identified in computer science education in Europe become far more apparent when examined in relation to the cognitive demands specific to extended reality (XR)–based learning environments. XR technologies– including virtual, augmented, and mixed reality–not only extend but fundamentally transform traditional digital technologies used in interactive learning contexts, generating new forms of interaction, meaning–making, and experiential engagement with knowledge. Current research shows that XR can create immersive three–dimensional environments that facilitate complex visualization and interaction, thereby supporting knowledge acquisition in ways that are largely inaccessible to traditional digital environments (Burke et al., 2025; Crompton et al., 2025).

One of the defining characteristics of XR environments is *presence*, often described in the literature as the feeling of "being there," which engages learners as active participants in an adaptive environment rather than as passive observers (Al–Samarraie et al., 2025). Presence involves a continuous perception–action–decision cycle, influencing learning processes by intensifying cognitive engagement and intrinsic motivation, as highlighted in analyses of cognitive factors within immersive learning models (Zhi et al., 2023).

A second essential feature of XR environments is *embodied interaction*, in which bodily movement, gestures, and spatial orientation constitute central modes of interaction. Recent studies indicate that XR applications employ a wide range of natural interaction techniques–such as gesture, motion, and voice–based interaction–which increase users' cognitive engagement and shape the ways in which they adapt their behavior during learning activities (Logothetis, 2025).

In this context, XR environments require learners to coordinate information originating from both the physical and digital worlds, particularly in augmented and mixed reality, where these layers coexist and dynamically influence one another. This coordination involves *spatial reasoning* processes manifested in the continuous construction and updating of complex mental models of space and interaction. Consequently, recent research highlights the potential of XR to support the investigation of cognitive processes in learning contexts that closely approximate real–world situations (González–Erena, Fernández–Guinea, & Kourtesis, 2025).

The *temporal dimension* further contributes to increased cognitive complexity in XR environments, where users' actions are followed by immediate system responses. This rapid coupling between action and feedback requires learners to observe the consequences of their decisions, evaluate them, and continuously adjust their interactions. As a result, XR environments demand more frequent decision making and more careful management of cognitive load than traditional problem–solving contexts, a finding confirmed by recent systematic reviews on the use of XR in education (Burke et al., 2025).

Taken as a whole, the dimensions of presence, embodiment, spatial reasoning, and real–time interaction reveal a set of cognitive demands that are only partially addressed by existing conceptualizations of computational thinking. While computational thinking provides a robust framework for problem analysis and abstract reasoning about systems, it does not conceptualize cognition as lived, spatial, and embodied experience. This limitation becomes increasingly evident as XR environments assume a more prominent role in education, including in the design of immersive learning systems.

XR environments introduce a higher volume of information and more complex learning situations by combining visual, spatial, and action–oriented elements within continuous interaction. This complexity requires learners to interpret information rapidly, evaluate the consequences of their actions, and avoid premature conclusions. In this context, alongside computational thinking, critical evaluation becomes essential, supporting informed decision making and cognitive self–regulation in immersive learning experiences.

Consequently, the cognitive characteristics of extended reality environments point to the need for a more comprehensive conceptual framework—one that connects algorithmic reasoning with the spatial, embodied, and experiential dimensions of thinking. At the same time, this perspective highlights the limitations of current computer science curricula and educational policies in preparing learners for immersive learning situations. In this regard, the findings reviewed here suggest research directions focused on understanding how cognitive processes adapt and reorganize when learning occurs in extended educational environments, beyond the traditional frameworks of digital thinking.

5. Systematic analysis of thinking models in the context of extended reality

The literature analysis aims to provide a critical evaluation of the main conceptual frameworks used to describe different models of thinking by examining how these models are defined and operationalized in scholarly research. The analysis focuses on three distinct yet interrelated domains: critical thinking, computational thinking, and the cognitive processes involved in extended reality (XR) contexts. The purpose of this analysis is to examine the extent to which existing models of thinking address the cognitive demands specific to immersive learning environments, thereby clarifying the adequacy of computational thinking and critical thinking in explaining and supporting cognitive performance in XR contexts.

Although critical thinking and computational thinking are well–established theoretical frameworks in both educational research and public policy documents, recent literature on learning mediated by extended reality technologies highlights the emergence of specific cognitive demands, such as spatial reasoning, embodied interaction, and the management of presence. In this context, the literature review examines theoretical arguments and empirical findings indicating changes in the conditions under which computational thinking is applied (Shute et al., 2017), as well as shifts in the function of critical thinking in XR environments, without assuming the existence of a distinct cognitive construct. From this perspective, processes such as spatial reasoning, multisensory integration, and real–time decision making are treated as contextual demands of XR environments that can be supported through adaptations of computational thinking tasks and through self–regulatory and evaluative mechanisms specific to critical thinking.

The literature review was guided by the following research questions:

1) What definitions and conceptualizations of critical thinking and computational thinking are present in educational and digital research?
2) Which cognitive processes are central to empirical research on learning and interaction in XR environments?
3) To what extent can critical thinking and computational thinking account for the cognitive demands identified in XR contexts?
4) What theoretical and empirical gaps suggest the need to adjust the operationalization and assessment strategies of computational thinking and critical thinking in XR contexts?

The systematic literature review was conducted in accordance with best–

practice recommendations for systematic reviews in education and the social sciences, as outlined in the PRISMA 2020 guidelines and in foundational methodological literature (Page et al., 2021; Siddaway et al., 2019).

To ensure comprehensive coverage of research in education, human–computer interaction, and immersive technologies, the ERIC (Education Resources Information Center) database was consulted. Only peer–reviewed journal articles and full papers published in peer–reviewed conference proceedings were included. The selected publications appeared between 2017 and 2025 and focused primarily on lower secondary, upper secondary, and higher education contexts.

Structured Boolean search strategies were applied by combining keywords related to:

(a) critical thinking;

(b) computational thinking;

(c) cognition in extended reality contexts (VR, AR, MR, XR).

This strategy enabled the identification of both conceptual frameworks and empirical studies conducted in educational and training settings.

The inclusion criteria required that studies:

(a) explicitly address thinking or cognitive processes;

(b) involve digital or XR environments;

(c) report conceptual models or empirical findings relevant to learning or cognitive performance.

The exclusion criteria eliminated editorial materials, purely technical studies lacking cognitive or educational relevance, clinically oriented research without transfer potential to educational contexts, and publications that did not meet standards of methodological rigor.

For the purpose of rigorous comparative analysis, studies were coded along three analytical dimensions:

- ✓ *Critical thinking* (CrT): evaluation, inference, argumentation, use of evidence (Shute et al., 2017);
- ✓ *Computational thinking* (CT): abstraction, decomposition, algorithmic thinking, automation, debugging (Angeli & Giannakos, 2020);
- ✓ *XR–specific cognition*: spatial reasoning, embodiment, multimodal processing, presence, real–time adaptation, and cognitive load management (Hsu et al., 2018; Johnson–Glenberg, 2018).

The application of this coding scheme facilitated the identification of both overlaps and gaps between existing *theoretical models of thinking* and the cognitive demands specific to extended reality environments.

In the context of immersive technologies used to support cognitive processes, the literature defines *cognitive augmentation* as the extension of human cognitive functions–such as attention, memory, and decision making–through active interaction with immersive digital environments (Johnson–Glenberg, 2018).

Recent research indicates correlations between the use of XR environments and improvements in spatial abilities, mental representation of three–dimensional objects, and long–term memory performance, compared to traditional learning environments (Alazmi, 2025). These outcomes are largely attributed to the high level of immersion afforded by XR, which enables learners to engage in complex tasks closely aligned with real–world application contexts (Radianti et al., 2020). The literature suggests that embodied interactions, supported by sensorimotor coupling, play a central role in shaping cognitive processes, extending beyond models based exclusively on symbolic processing (Johnson–Glenberg, 2018).

In educational contexts, studies indicate that XR environments can support deep learning through active engagement, reflection on action, and the strengthening of learners' confidence in their own decisions, thereby facilitating the transfer of competences across learning and application contexts (Jensen & Konradsen, 2018; Makransky et al., 2021).

At the same time, recent studies highlight the risk of cognitive overload associated with poorly designed XR environments. In this regard, the application of cognitive load theory principles becomes increasingly important to balance the benefits of immersion with learners' processing capacities (Sweller, 2020; Makransky & Petersen, 2019).

Analysis of literature published after 2017 reveals a marked increase in interest in cognition in XR environments, particularly from 2020 onward. Most studies adopt empirical approaches, focusing on specific cognitive dimensions such as spatial reasoning, attention, and memory retrieval (Radianti et al., 2020). The field is predominantly interdisciplinary, with educational research increasingly informed by cognitive psychology and immersive technologies.

Thematic synthesis of the recent literature identified four central directions:

(1) the role of spatial and embodied cognition in XR environments;

(2) multimodal interaction as a driver of cognitive stimulation;

(3) presence and immersion as mediators of learning effectiveness;

4) the need for adaptive cognitive support to manage task complexity.

These dimensions are weakly represented in classical computational thinking frameworks.

Overall, the synthesis highlights a conceptual gap between traditional models of thinking and the cognitive demands of XR environments. While the computational thinking paradigm offers a comprehensive model for algorithmic problem solving

(Angeli & Giannakos, 2020), it provides only partial explanatory power in immersive contexts.

Overall, the literature analysis clarified the principal definitions of critical thinking and computational thinking used in educational research and identified the cognitive processes examined in studies of learning and interaction in XR environments. The findings indicate that, although computational thinking and critical thinking can partially account for the cognitive demands of these environments, they exhibit limitations when applied in their traditional forms to contexts characterized by spatiality, embodiment, and real–time interaction. The literature therefore points to theoretical and empirical gaps that suggest the need to adjust the operationalization and assessment of these frameworks, particularly through interaction–based tasks, modelling and simulation activities, and decision making under conditions requiring real–time adaptation.

In this context, the results underscore the explanatory limits of the computational thinking paradigm when applied in its traditional form to immersive learning contexts. While computational thinking provides a robust framework for algorithmic problem solving and digital system modelling, the reviewed literature indicates the need to adapt its operationalization and assessment in XR tasks, as well as to strengthen the role of critical thinking as a mechanism for evaluation, justification, and reflection on decisions and evidence in immersive interaction contexts.

The main findings of the systematic review, categorized by the analytical dimensions and their implications for the proposed framework, are synthesized in Table 3.

Table 3. Synthesis of the literature across reviewed dimensions and the proposed conceptual framework

Dimensions	Relevant sources	Key findings from the literature	Integration into the proposed conceptual framework
Computational Thinking (CT) and curricular gaps	Bocconi et al. (2016, 2022); Eurydice (2022); Angeli & Giannakos (2020); Digital Education Action Plan 2021–2027 (European Commission, 2021).	CT is predominantly centred on algorithms and programming, while modelling and human–system interaction are marginalised.	Defines the need to extend CT through XR environments in order to address modelling and simulation domains.
Embodied and spatial cognition	Johnson–Glenberg (2018); Hsu et al. (2018); Logothetis et al. (2025);	Gestures, movement, and spatial orientation are essential for learning in XR environments.	Proposes a shift in CT from symbolic manipulation (code) toward problem solving

	Radianti et al. (2020)		through physical–virtual interaction.
Presence, immersion, and cognitive load	Makransky et al. (2019, 2021); Sweller (2020); Jensen & Konradsen (2018); Johnson–Glenberg (2018);	Immersion increases presence but may lead to cognitive overload, reducing resources available for learning.	Positions CrT as a self–regulatory mechanism for managing attention and cognitive resources in complex environments.
Multimodal assessment and training	Shavelson et al. (2019); González–Erena et al. (2025); Alazmi & Alemtairy (2024)	XR enables real–time assessment of users' behaviours and affective responses in simulated real–world situations.	This supports moving assessment from code to decision–making in XR
Critical Thinking (CrT) as a regulatory mechanism	Facione (2023); Halpern & Dunn (2022); Shute et al. (2017)	CrT involves analysing available information, identifying errors, and justifying decisions under conditions of uncertainty.	Positions CrT as a validation mechanism for solutions generated through CT, supporting reflection on consequences.
Analysis of trends and affective responses in XR	Al–Samarraie et al. (2025); Burke et al. (2025); Radianti et al. (2020); Zhi & Wu (2023)	A correlation is identified between the level of immersion and learners' affective responses, highlighting the role of perceived presence in learning task success.	Justifies the integration of CrT mechanisms to balance affective and intuitive reactions, ensuring reflective application of CT processes in dynamic learning environments.

6. Reconfiguring computational thinking and critical thinking in extended reality contexts

There is a growing need to reconsider the role of computational thinking in the contemporary digital classroom in light of the transformations introduced by extended reality (XR) environments in the ways learners interact with information, solve problems, and make decisions (Shute, Sun, & Asbell–Clarke, 2017; Crompton et al., 2022). Within this context, it becomes particularly relevant to examine how computational thinking and critical thinking can be integrated into a coherent approach capable of addressing the cognitive demands of digital literacy in a dynamic, immersive, and interactive environment (Facione, 2023; Makransky & Petersen, 2019).

In XR environments, learners receive immediate feedback in response to their actions, which directly influences how situations are interpreted and decisions are made (Radianti et al., 2020; Makransky et al., 2021). Under these conditions, learners may make rapid decisions based on elements that attract immediate attention within the immersive space, potentially leading to misinterpretations or unwarranted generalizations (Dede, 2017). In this context, critical thinking functions as a self–regulatory mechanism that tempers intuitive reactions and supports deliberate evaluation of information and outcomes, thereby complementing the procedural function of computational thinking (Facione, 2023; Halpern, 2014).

From an operational perspective, critical thinking in XR environments can be observed and assessed through indicators such as:

(a) explicit formulation of hypotheses and verification criteria;

(b) justification of the chosen course of action in relation to task objectives;

(c) comparison of alternative options and justification of the selected approach;

d) identification of errors–whether user or system–related and revision of decisions;

(e) reflection on the consequences of actions, including considerations of safety, equity, and user impact.

Integrating these indicators into the design of XR tasks strengthens the role of critical thinking as a mechanism for validating and regulating the application of computational thinking in immersive contexts (Facione, 2023; Shavelson et al., 2019).

Computational thinking emerged in response to the increasing pervasiveness of computational systems in the world. Its abstract, algorithmic, and structured nature can be understood as a cognitive approach tailored to environments in which interaction with reality is mediated primarily through symbolic representations and formal procedures. This approach enables highly effective understanding and design of computational systems and continues to play a central role in computer science education (Shute et al., 2017; Angeli & Giannakos, 2020). In XR educational contexts, however, these characteristics must be aligned with processes of critical analysis, information evaluation, and reflection on the consequences of decisions–processes that are intrinsic to critical thinking.

Extended reality environments fundamentally alter this relationship. In XR contexts, learners no longer conceptualize or manipulate computational processes from an external standpoint; instead, they enter and inhabit environments in which physical and virtual components coexist and interact. Cognition unfolds through perception, movement, and real–time interaction, requiring learners to continuously coordinate multiple streams of information. This shift reconfigures problem–solving activity, moving it away from abstract and sequential modes of reasoning toward context–dependent and dynamic forms of cognition (Johnson–Glenberg, 2018; Makransky et al., 2021).

From this perspective, extended reality environments require a contextualized application of computational thinking competences, complemented by the regulatory mechanisms of critical thinking. Abstraction remains a central process, but it is enacted in relation to spatial and experiential structures rather than exclusively symbolic ones (Crompton et al., 2022; Radianti et al., 2020). Decomposition involves breaking down complex environments and interactions into manageable components, while algorithmic thinking manifests through the anticipation of interaction patterns and the consequences of actions. Within this framework, critical thinking supports decision evaluation, information validation, and reflection on the learning experience.

This complementary relationship between computational thinking and critical thinking in extended reality contexts is synthesized in Table 4, which highlights the distinct yet interrelated roles of the two cognitive frameworks in XR–based learning activities.

Table 4. Manifestations of computational thinking and critical thinking in extended reality contexts

Dimension	Computational Thinking (CT) in XR	Critical Thinking (CrT) in XR
What learners do	Construct models and define rules governing system behaviour and interaction	Analyse choices made and evaluate the outcomes obtained
Relation to the environment	Engage in controlled interaction with digital elements	Develop a holistic understanding of the situation and judge actions in relation to context
Decision–making	Follow clearly defined, step–by–step procedures	Continuously adjust decisions based on ongoing observation and feedback
Role in thinking	Supports the organisation and procedural resolution of problems	Supports verification, correction, and reflective evaluation of solutions
Validation of results	Test whether the solution functions correctly and debug errors	Justify conclusions and solutions through argumentation
Responsibility and consequences	Focus on achieving a functional solution	Evaluate risks and the impact of decisions on users and the learning context

Table 4 highlights that XR environments do not imply a replacement of computational thinking, but rather an expansion of the contexts in which it is applied. Within such environments, computational thinking retains its central role in modelling, structuring, and anticipating the behaviour of digital systems, while critical thinking becomes essential for evaluating decisions, interpreting information, and reflecting on the consequences of actions within an immersive and dynamic context.

More fundamentally, this shift forms part of a broader paradigmatic transformation in how knowledge is produced and used in computationally mediated spaces. While computational thinking remains well aligned with epistemological frameworks that prioritise representation, formalisation, and control, XR environments amplify the importance of experience and direct interaction, thereby necessitating the systematic integration of critical thinking processes into learning activities.

From this perspective, the use of XR environments underscores the need for an integrative educational approach in which computational thinking is supported by critical thinking, enabling learners to analyse complex situations, justify decisions, and reflect on immersive learning experiences. Preparing learners for contemporary digital ecosystems must therefore be grounded in a solid foundation in computational thinking, alongside the development of competences related to critical evaluation and cognitive self–regulation.

Overall, the literature analysis has clarified how computational thinking and critical thinking are defined within educational research and has identified the core cognitive processes examined in XR environments. The findings indicate that, although these frameworks partially account for the cognitive demands of immersive learning, they become limited when applied in their traditional forms. In this context, the literature points to the need to adapt both the evaluation and application of these frameworks through tasks that involve interaction, modelling, and decision making under dynamic conditions.

7. Educational implications for European curricula

Extended reality (XR)–based learning environments introduce significant changes for curricular developments in European computer science education. Although current curricula have effectively supported computational thinking as a foundational skill, the emphasis has been placed primarily on abstract algorithmic reasoning (Bocconi et al., 2016; Bocconi et al., 2022; Angeli & Giannakos, 2020). The integration of XR technologies into education highlights the need to reconsider curricular priorities so that educational objectives respond more adequately to emerging cognitive and pedagogical demands, through a balanced and coherent articulation of computational thinking and critical thinking (European Commission, 2021).

7.1. Implications for Curriculum Design

At the curricular level, the integration of XR environments underscores the need to move beyond the predominant focus on algorithms and programming toward a more balanced representation of the various domains of computer science.

Analyses conducted by Eurydice indicate that areas such as modelling and simulation, design and development, and human–system interaction remain insufficiently represented in many European curricula, despite their increasing relevance for interactive and immersive digital contexts (Eurydice, 2022; Bocconi et al., 2022).

From an applied perspective, this shift entails embedding computational thinking competences within educational activities carried out in XR environments, alongside the systematic development of critical thinking, which supports decision evaluation, information interpretation, and reflection on learning experiences. In particular, at the upper secondary level, students can be engaged in modelling, simulation, and design tasks that require both algorithmic reasoning and critical analysis in dynamic and situated contexts (Facione, 2023; Halpern & Dunn, 2022).

7.2. Pedagogical Implications

From a pedagogical standpoint, XR environments support the development of educational approaches centred on learning through interaction and experience. In these contexts, simulation and exploratory activities align with constructivist and experiential learning models, in which understanding is constructed through action, reflection, and real–time feedback.

Integrating XR technologies into teaching practice does not imply abandoning algorithmic thinking or formal problem–solving approaches. On the contrary, effective instruction requires the continuous articulation of computational thinking with critical thinking. For example, learners may use computational thinking to analyse a problem and construct a model, while employing critical thinking to evaluate the model's behaviour within an XR simulation, reflecting on the consequences of decisions made and on the validity of the results obtained (Makransky et al., 2020; Shavelson et al., 2019).

7.3. Implications for initial teacher education and professional development

The use of XR environments is particularly relevant in the context of initial teacher education and continuous professional development. European reports consistently emphasise the central role of teachers in implementing computer science curricula and highlight the challenges associated with preparing educators to teach emerging digital competences (European Commission, 2021; Bocconi et al., 2022).

Within this framework, teacher education programmes should aim to develop competences in designing educational activities that coherently integrate computational thinking and critical thinking in XR contexts. This includes providing teachers with direct hands–on experiences with immersive technologies, as well as opportunities for pedagogical reflection on their effective use in teaching and learning processes (Jensen & Konradsen, 2018).

7.4. Alignment with European educational policy frameworks

The integration of XR environments into computer science education is fully aligned with European policies on digital competence, innovation, and future–oriented education. European strategies seek not only to develop technical skills but also to strengthen cognitive capacities related to problem solving, critical analysis, and adaptation to rapidly evolving technological contexts (European Commission, 2021).

From this perspective, leveraging XR environments as educational spaces supports the application of computational thinking and critical thinking in authentic learning situations, contributing to the development of advanced digital competence. Such an approach promotes a forward–looking vision of computer science education and provides a coherent framework for adapting European curricula to the demands of contemporary digital ecosystems.

8. Conclusions and future research directions

The findings of this study indicate that *traditional cognitive models do not adequately capture the learning processes occurring in extended reality (XR) environments*, which are characterized by immersion, presence, and real–time interaction. In this context, *computational thinking, when applied in isolation, proves insufficient*, making it necessary to complement it with evaluative, reflective, and interpretative processes associated with critical thinking.

The analysis of computer science curricula across Europe reveals notable *gaps in domains that are essential for XR–based learning*, such as modelling and simulation, design and development, and human–system interaction. These findings support *the need for a closer articulation between computational thinking and critical thinking*, without introducing a new cognitive construct.

The main contribution of this paper lies in *proposing an integrative perspective that explains how these two forms of thinking complement each other in supporting cognitive performance in XR environments*. From an educational standpoint, the results point to *significant implications for curriculum design, pedagogical strategies, and teacher education*.

Further empirical studies are needed to examine the development of computational thinking and critical thinking in XR contexts, as well as to evaluate educational interventions based on modelling, simulation, and critical reflection. In addition, future research may explore the influence of different types of XR environments and investigate ways to systematically integrate these cognitive processes into existing digital competence frameworks.

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