Extended Reality Thinking: Why Interacting in XR Environments Calls for New Cognitive Skills

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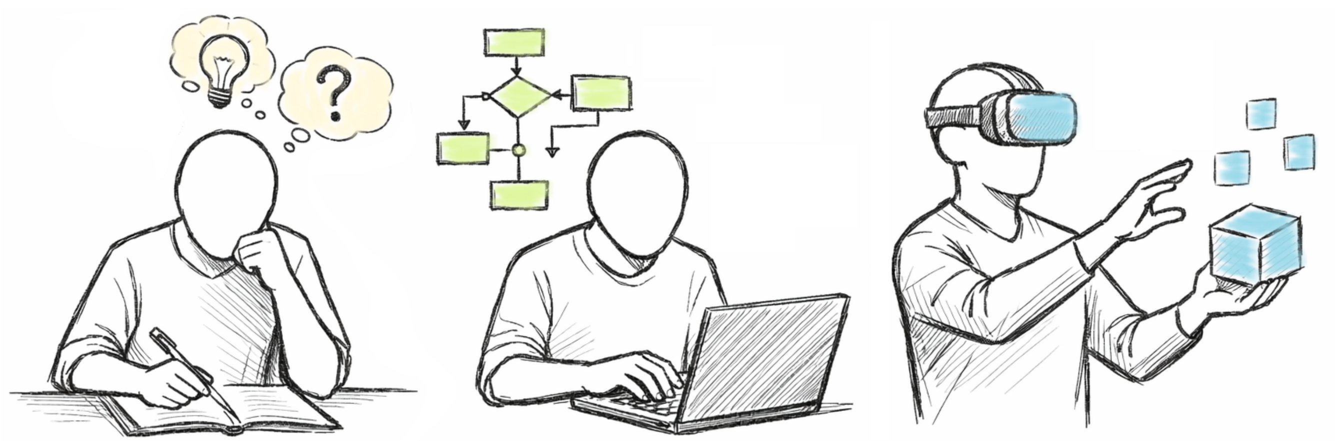

Figure 1: A critical thinker (left) engages in reflective inquiry and logical reasoning; a computational thinker (middle) reasons using computational concepts, models, and tools; in contrast, an extended reality thinker (right) reasons with multiple mental models about presence across different realities, object manifestations, and transitions between realities. From left to right, as computing increasingly permeates our environments, new and more sophisticated forms of reasoning become necessary.

Abstract

We introduce *extended reality thinking* as a complement to critical and computational thinking to address the distinctive context in which users reason about perception, action, and presence in XR worlds. Specifically, we identify a triad of *worlds, objects* within worlds, and *transitions* across worlds as core dimensions along which an extended reality thinker evaluates their experiential and perceptual state. We illustrate the relevance of extended reality thinking through two examples drawn from prior studies that examined perceptual and attentional differences when interacting with physical vs. virtual displays. By further operationalizing extended reality thinking within XR interaction design, the scientific community can more effectively ground technological advances in an understanding of the cognitive skills users must apply when engaging in hybrid physical-virtual environments.

CCS Concepts

• **Human-centered computing → Mixed / augmented reality**; **Virtual reality**; **HCI theory, concepts and models**.

CHI EA '26, Barcelona, Spain

ACM ISBN 979-8-4007-2281-3/2026/04
https://doi.org/10.1145/3772363.3798484

Keywords

Extended reality, critical thinking, computational thinking, perception, presence, virtual reality, mixed reality, augmented reality

ACM Reference Format:
Radu-Daniel Vatavu. 2026. Extended Reality Thinking: Why Interacting in XR Environments Calls for New Cognitive Skills. In *Extended Abstracts of the 2026 CHI Conference on Human Factors in Computing Systems (CHI EA '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3772363.3798484

1 Introduction

Our physical environments have become increasingly digitally augmented through the integration of computer technology in virtually all aspects of modern life, enabling ubiquitous computing [32] and extended reality (XR) [3] experiences. One consequence of this computational transformation is that living in a computerized world requires a distinctive set of cognitive skills for problem solving, capitalizing on the core nature of the computers themselves. This need was formalized through computational thinking [1,9,41], i.e., formulating problems and solutions through computational models, which emerged as a necessary complement to critical thinking [22].

However, when going beyond the physical world, as in XR environments, both critical and computational thinking paradigms reveal limitations caused by distinct cognitive challenges. These include building effective mental models for navigating diverse physical-virtual worlds [2], adapting to physical objects with changing representations [33], constructing and operating on dynamic mappings between physical and virtual [34], experiencing physical objects as digital entities [10], and conceptualizing presence when transitioning across realities [31]. Unfortunately, critical thinking does not encompass the formal specification and automation of procedures [17], central to the behavior of virtual objects in programmable realities [37], where both world appearance and functionality are customizable through computation; and computational thinking becomes challenged when its typical assumptions of stable representations and predictable state transitions no longer apply due to alternative laws of physics and causality in XR [5].

In this context, we argue that a distinctive set of cognitive skills is required to effectively reason about novel XR experiences, where stimuli originate from physical and virtual worlds of different ontological and perceptual nature. To this end, we propose *extended reality thinking* as a complement to critical and computational thinking, and identify three core dimensions—*worlds, objects,* and *transitions*—that reflect the ontological status, affordances, and dynamics of change of reasoning about perception, action, and presence in XR environments. We illustrate the relevance of extended thinking with two examples involving hybrid physical-virtual interactions.

2 Critical and Computational Thinking

In this section, we provide an HCI perspective on critical (Subsection 2.1) and computational (Subsection 2.2) thinking as foundational frameworks on which extended reality thinking builds. In Section 3, we present our arguments for extended reality thinking, followed by illustrative examples in Section 4.

2.1 Critical Thinking

With philosophical roots in Socrates' elenchus method of questioning [15], aimed at exposing contradictions in an interlocutor's beliefs, critical thinking emphasizes logic, clarity, and relevance through a cognitive process in which available evidence is scrutinized to reach justified conclusions. Later articulated in Dewey's notion of reflective thinking [13], it became established as an educational method consisting of decomposition of problems, identification of assumptions, collection of evidence, providing justifications, comparison of perspectives, and tracing out implications. According to Glaser [12], critical thinking involves a triadic construct of disposition toward thoughtful inquiry, knowledge of methods of logical reasoning, and the skills to apply them; see Ennis [11] for a survey of perspectives, from Dewey's reflective roots to Glaser's triadic formulation to the broader sense of objective analysis.

In HCI, critical thinking manifests through users' reflective and evaluative engagement with computer systems. Notable examples include sensemaking [21] (where users structure and reinterpret information to construct understanding, act effectively, and give meaning to their experiences), epistemic interaction [39] (where users employ external representation, appropriation, and abductive reasoning to manage complexity), and design for reflection [4] (where interactive systems are intentionally designed to support reflective and evaluative reasoning), which align with central dimensions of critical thinking and operationalize it in interactive contexts. For example, a user may engage in critical thinking by reflectively assessing whether the realism of their virtual avatar representation in social XR aligns with social norms and the anticipated interpretation of others, and revise it accordingly [20].

However, by privileging rational assessment, reflection, and epistemic evaluation, critical thinking does not encompass automated execution of procedures characteristic of computation [17] which, once formalized, can proceed without reflective judgment. In this sense, it is complemented by computational thinking [22], which introduces design of automated processes to expand the space of inquiry beyond what critical thinking alone can sustain; see next.

2.2 Computational Thinking

Wing [41] proposed computational thinking as a universally applicable attitude and skill set for problem solving, drawing on concepts fundamental to computer science. Historically grounded in algorithms design [7], computational thinking is applied to real-world problems by formulating them in ways that admit algorithmic solutions [1], which convert inputs to desired outputs through computational doing and supported by computational design [8]. In this context, clearly separated from doing and designing, computational thinking covers "the mental skills and practices for *designing* computations that get computers to do jobs for us, and *explaining* and interpreting the world as a complex of information processes" [9, p. 4]. More broadly, Hu [18] frames it as a hybrid thinking paradigm that integrates different modes of thinking—logical, algorithmic, scientific, mathematical, analytical, engineering-oriented, and creative—in a unifying perspective that amplifies each through computational concepts and automation.

In HCI, computational thinking is primarily reflected in the paradigm of computational interaction [28], which relies on abstraction, automation, and analysis to inform the design of interactive systems. Computational interaction involves building models from observed user data, devising and applying algorithms to exploit models for synthesizing designs, automating the modeling process, and simulating user-system behavior; for example, Transcalibur [33] is a hand-held VR controller, developed using a data-driven computational perception model, that can dynamically alter its mass properties to create the illusion of holding specific shapes. Users exercise computational thinking by conceptualizing interactive tasks as procedural sequences, as in stepper tutorials for mixed-initiative learning of interfaces [24]. In such systems, interaction is governed by explicit control structures similar to those of reversible programming language steppers, enabling users to reason about actions, state transitions, and outcomes in relation to the interactive system.

2.3 Summary

Critical thinking emphasizes evaluation, judgment, and reflection grounded in evidence, whereas computational thinking favors procedural reasoning and specification of automated processes. The two are complementary, with the latter expanding cognitive practices through computational methods, tools, and resources. Computational thinking is particularly well suited to a physical world with increasingly integrated computers, including those that become invisible in Weiser's [40] sense. In such environments, computational thinking is fundamental for operating effectively and has been recognized as a foundational skill, on par with reading, writing, and arithmetic [41]. Nevertheless, the scope of computation is typically grounded in a single, physical world, where computational thinkers design and deploy algorithmic-based systems to "get computers to do jobs" that ultimately refer back to stable and predictable physical contexts [9]. Next, we introduce extended reality thinking for perceptual experiences spanning different worlds.

3 Extended Reality Thinking

XR environments involve an interplay of physical and virtual objects that modifies perception and action, thereby affecting both critical and computational thinking and revealing their context-specific limitations. For example, while critical thinking can be applied to distinguish virtual from physical stimuli, the evidence available in XR is inherently determined by the synthetic environment's photorealism [36] and the user's sense of presence [25]. A classical example is exposure to phobic stimuli, such as a virtual spider: although the user knows the spider is not real, they nonetheless experience physiological and emotional reactions as if it were. On the other hand, computational thinking can be challenged by XR worlds when assumptions of algorithmic predictable state transitions no longer straightforwardly apply. For example, an algorithmic solution developed within one world may not translate across another with different laws of physics, time, and causality [5], such as when engaging in cross-reality transitions [31]. In these cases, procedural reasoning must explicitly account for variability in the underlying world model, formalized by Milgram and Kishino's [25] Extent of World Knowledge dimension, placing constraints on computational thinking that were unnecessary in physically-grounded contexts. Moreover, prior work has showed that virtual and physical embodiments elicit distinct cognitive frames (i.e., mental templates that people use to organize, interpret, and act on encountered information), resulting in different expectations, forms of engagement, and interaction outcomes [26].

In this context, we argue that operating effectively in XR environments requires a distinct and systematic set of skills—*extended reality thinking*—to support reasoning in hybrid settings. By centering on a triad of considerations—worlds, the objects they contain, and transitions across these worlds—we integrate ontological status [25], object affordances [27], and dynamics of change [14] to identify three dimensions central to extended reality thinking:

- ***The world dimension:*** *Reasoning about the nature of the extended reality and one's presence within it.* According to the Reality-Virtuality continuum [25], many possible mixed-reality worlds can be created, triggering different extents of felt presence in users. This possibility introduces substantially greater complexity compared to situations in which only a single, stable physical world is involved, requiring adaptation to different laws of physics, timing, and causality [5], different relationships with the physical world [34], and even different technological means [6,42] for the users themselves to change the appearance and functionality of realities that become programmable [37].
- ***The object dimension:*** *Reasoning about the nature of objects and the experiences they enable.* When the physical layer integrates with the virtual, their conjoint perception can be programatically mediated. For example, touching a physical surface may be accompanied by surprising, non intuitive haptic sensations [38], physical objects can dynamically change their mass properties to generate different perceived virtual shapes [33], virtual objects come into material existence through physical telepresence [23], physical and virtual objects are aligned for the best possible visual-haptic experience [16], physical objects can be equipped with the ability to interact as if they were digital [10] and turn into animated talking characters that respond to users [19]. This multiplicity of affordances is intrinsic to the very nature of hybrid physical-virtual objects in XR environments.
- ***The traversing dimension:*** *Reasoning about navigating through different realities and object representations.* The flexibility in worlds and objects results in the possibility of switching between them and, thus, traversing across experiences of presence and perception. For example, a user watching a movie can switch the nature of the mixed-reality visualization from a virtual TV screen to characters existing the screen into the room to fully immersing in the movie [30]. More generally, cross-reality systems offer the possibility of experiencing different or changing actualities(i.e., the actual manifestations of the reality that users experience [2]) when transitioning throughout various combinations of the physical and virtual [31].

Along these dimensions, an extended reality thinker dynamically reasons about their presence across XR worlds, mentally manipulating physical-virtual mappings and object manifestations, while tracking the different computational models that govern each traversed reality. This form of reasoning involving ontological dynamics expands on both critical and computational thinking and motivates its own distinct set of skills. Next, we show two examples.

4 Examples

We discuss how extended reality thinking manifests differently from computational and critical thinking with two use cases selected from the scientific literature on interactions in the virtual vs. physical world. In the first example [38], we focus on touch input performed on both a physical and a virtual display; in the second [29], we address attentional aspects involving visual content on a physical vs. virtual display; see Figure 2 for illustrations.

4.1 Example #1: Touch Input on Physical and Virtual Displays

Terenti et al. [38] conducted a study to examine the user experience of vibrotactile feedback accompanying touch input on a large physical display, which they contrasted with the experience reported for a virtual display (Figure 2, left). Touching a target on a physical display, seemingly an atomic task due to frequent use, requires precise visuomotor planning: following visual search, the arm starts an accelerated trajectory while the wrist rotates and the finger stretches to reach the display's surface, pressure is applied by positioning the finger within the target's boundary, followed by finger lift off and arm retraction. In this process, critical thinking is engaged when users reflect on their performance and subjective experience, e.g., "Was I successful?" and "How did I feel?" Computational thinking is

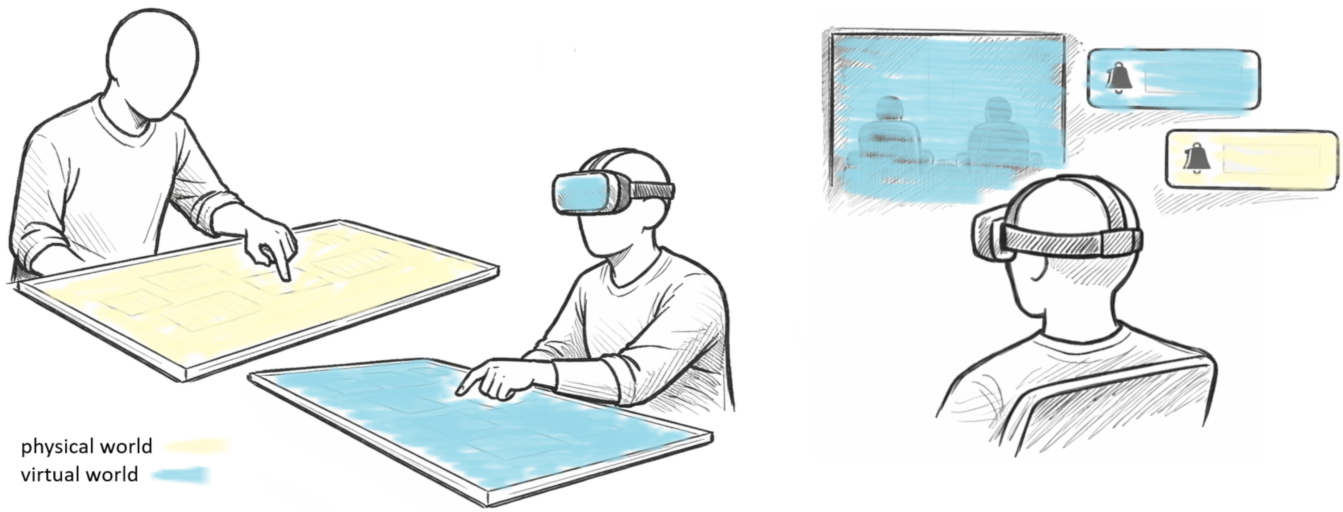

Figure 2: *Left:* Input on a physical vs. virtual display [38]; *Right:* Attention to notifications in the virtual and physical worlds [29].

applied when users conceptualize the interactive task as a sequence of steps with a conditional outcome in terms of haptics.

Terenti et al. [38] noted similarities in users' reported experience between physical and virtual displays, but also a statistically significant difference in perceived efficiency, with the physical display evaluated as more efficient than the virtual one. While world presence was at its peak during interactions with the physical display, a disconnection was present between visual stimuli in the virtual world (target, display, and hand) and vibrations on the physical body. This experiential difference highlights the role of extended reality thinking, which goes beyond reflecting on task performance and subjective experience (critical thinking) and conceptualizing procedural steps and conditional logic of the interaction (computational thinking) to enable reasoning about stimuli originating from two worlds of different ontological and perceptual nature.

4.2 Example #2: Attention to Notifications Presented on Physical and Virtual Displays

Pamparău et al. [29] conducted a visual attention study, where participants were asked to maintain focus on a movie presented on a HoloLens device while notifications were displayed at random times in the visual periphery. Following the movie requires sustained visual attention that is periodically affected by peripheral stimuli with both sequential and concurrent subtasks: maintaining attention to the movie while monitoring the periphery, detecting the onset of a notification and shifting attention, reading its content, returning attention to the primary task, while retaining all notifications for later recall. In this process, critical thinking is engaged when users reflect on their performance, e.g., "Have I understood the notification?," "Do I remember the other notifications?" The interaction can also be described with computational thinking, such as concurrency and resource constraints, as the subtasks take place in parallel under limited attentional bandwidth.

Pamparău et al. [29] reported similar user perception and comparable performance in understanding and recalling notification content in both the virtual and physical conditions. The only statistically significant difference was faster reaction times when notifications were delivered in the same virtual world as the movie, which the authors explained by lower cognitive demands arising from not having to manage attention across two worlds. Reaction time may thus reflect differences from transitions: in the virtual world, movie and notifications coexist; in the physical-world condition, context switching requires not only an attentional shift, but also a transition between worlds. This performance difference highlights the relevance of extended reality thinking, understood here as the ability to reason about and coordinate visual stimuli from two different worlds while managing transitions between them.

4.3 Practical Implications

In these examples, users engage in reasoning about *worlds, objects,* and *transitions*, according to the triad of extended reality thinking. In the world dimension, touching a target on a virtual display requires alignment between the movement of the virtual hand and haptic cues delivered on the physical hand, revealing an extended physical-virtual space; similarly, the split attention when notifications are rendered on a physical display requires an expanded-world mental model. In the object dimension, virtual targets are perceived visually within the virtual world and through haptic cues outside it. In the transition dimension, notifications on a physical display require continuous switching of attention across two worlds. Unlike critical or computational thinking, extended reality thinking accounts for these perceptual, ontological, and procedural complexities of interacting in hybrid physical-world environments, which warrants its own distinct formalization.

By explicitly considering these three dimensions in their interactive prototypes, researchers and practitioners can better identify and support the cognitive skills required in users for effective presence and interaction in XR worlds. In practice, this means mapping interaction characteristics, such as sequential vs. concurrent structures, to the worlds, objects, and transitions they entail. For instance, in our first example, interaction is sequential with respect to the target object (a selectable item on a physical or virtual display), whereas in the second it is concurrent (attending to notifications on a physical or virtual display), revealing distinct perceptual-action models. In the first case, conditional logic depends on final feedback at the specific moment of finger lift-off; in the second, it depends on events with uncertain occurrences originating in the surrounding world. Accordingly, the first interaction prioritizes perceptual alignment between action and feedback, whereas the second attentional switching when feedback emerges from a different world, requiring a cognitive transition. These contrasts, sequential vs. concurrent, deterministic vs. stochastic, perception-optimized vs. reaction-optimized, illustrate the need for different cognitive skills that enable users to act efficiently and feel present in the XR environment. Such processes can be anticipated during design, supported through interaction techniques, and assessed during evaluation.

Designers can implement cues that clarify interaction states and support users in managing transitions across worlds, enabling reasoning about and acting within superimposed physical-virtual experiences structured by *worlds, objects,* and *transitions*. For example, experimental design in extended reality thinking could isolate specific cognitive skills by manipulating XR characteristics as independent variables, such as world structure (e.g., single vs. dual vs. multiple-world environments), distinguishing objects by the cross-world interactions they afford (e.g., sequential vs. concurrent), or modeling world transitions explicitly for perceptual-action tasks (e.g., transition properties as experimental conditions). Traditional metrics of presence, immersion, and task efficiency can be complemented by measures of cognitive costs associated with transitions, such as the time required to shift attention across worlds, or for correctly identifying the world to which an object belongs, i.e., ontological clarity regarding an object's nature and origin. Furthermore, traditional constructs in human-computer interaction, such as spatial awareness and task switching, can be reconceptualized as cross-world reasoning and ontological switching to explicitly address cognitive skills in extended reality thinking.

5 Conclusion

We proposed extended reality thinking as a complement to critical and computational thinking to address reasoning in XR worlds that deliver complex experiences through world presence, object affordances, and the ability to navigate across multiple realities. Interesting future work lies ahead to formalize extended reality thinking with a structured conceptual space, methods for integrating it in designing XR worlds, interactions, and experiences, and operationalizing it through dedicated measures of user performance, decision-making, and self-reflection in XR. Designing studies that treat worlds, objects, and transitions as experimental variables will enable formal investigation of users' extended reality reasoning toward empirical insights to further inform the theory and practice in XR interaction design.

Use of AI-generated Images

Figures 1 and 2 were created using GPT-5-mini[1] with prompts specifying abstract representations and faceless figures to avoid accidental resemblance and minimize biases of gender, race, or technical background. According to the ethics of AI-generated figures [35], these images are intended as "illustrative, not aiming at an authoritative depiction" in terms of communicative purpose, and their type/function is "introductory illustration." The figures were subsequently edited manually to remove unnecessary decorative elements and emphasize key elements using color.

[1] https://developers.openai.com/api/docs/models/gpt-5-mini

Acknowledgments

This work was supported by a grant of the Ministry of Education and Research, CCCDI-UEFISCDI, project number PN-IV-PCB-RO-MD-2024-0130, within PNCDI IV.

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