Wicked Problems, Provocations, and Design Orientations in AI-Augmented Extended Reality for Embodied Computer Science Learning

Chih-Pu Dai[1], Bryan Kim[2], Meng Xia[3], Jong-in Lee[2], Seung Won Yoon[1], and Tracy Hammond[3]

[1] College of Education & Human Development, Texas A&M University, College Station, TX, USA
cdai@tamu.edu
[2] College of Visualization, Performance and Fine Arts, Texas A&M University, College Station, TX, USA
[3] Computer Science & Engineering, Texas A&M University, College Station, TX, USA

Abstract. Extended reality (XR) promises rich, immersive learning experiences, which can be further augmented by artificial intelligence (AI). However, designing AI-augmented XR for abstract Computer Science (CS) concepts remains underexplored and lacks established design knowledge. We adopt a Research through Design (RtD) approach to investigate how embodied interaction and AI-driven feedback can jointly support CS education. Through iterative prototyping of XR learning activities, our work surfaces five "wicked" design challenges at the intersection of XR, AI, and embodied CS learning. For each challenge, we present a provocation—posed as a critical question—and articulate an emerging design orientation as a potential response. Together, these contributions provide an initial conceptual framework and practical insights in this nascent domain to guide designers and researchers in developing AI-augmented, embodied learning environments for CS education.

Keywords: Artificial Intelligence · Extended Reality · Computer Science Education · Embodied Learning · AI Feedback Systems

1 Introduction

Recent advances in extended reality (XR) and artificial intelligence (AI) have expanded how teaching and learning experiences can be designed. Beyond their conceptual promise, progress in computing power, graphics, sensing, and AI algorithms has made these technologies increasingly accessible for educational use [35, 1]. Together, XR and AI offer new opportunities for immersive and personalized learning experiences that extend beyond traditional classrooms, particularly for broadening access to Computer Science (CS) education [35, 13, 10]. However, despite this potential, it remains unclear how XR and AI can be effectively designed and integrated into educational settings from a human–computer interaction (HCI) perspective.

Prior work in CS education has leveraged technologies to support learning of abstract concepts—such as algorithms and data structures—primarily through symbolic and code-based representations [19, 25]. In contrast, XR research has shown that immersive and embodied interaction can support STEM learning by engaging spatial, motor, and perceptual processes [1], while AI-driven learning systems have increasingly been used to provide adaptive feedback and personalized scaffolding [3]. There is a growing interest in applying these approaches to CS education.

Although interest is growing in applying these approaches to CS education, design knowledge at their intersection remains fragmented and under-theorized. This fragmentation gives rise to recurring design tensions for pedagogically sound, cognitively manageable, and experientially faithful systems that resist straightforward solutions.

Therefore, in this paper, we asked: **(RQ1)** What are the unique wicked problems and challenges in designing AI-augmented XR experiences for CS education? and **(RQ2)** What emerging design orientations can help navigate these problems in AI-augmented XR experiences for CS education?

2 Related Work

Computer Science Education and AI. The widespread availability of large language models (LLMs) has accelerated their uptake in CS education, particularly as programming assistants in introductory courses and classroom settings [33, 19]. In these settings, a recurring concern is whether LLM support operates as a scaffold that sustains students' reasoning or as a shortcut that displaces it. There are practical and pedagogical design constraints for classroom integration: when LLMs are introduced, how their use is aligned with learning goals and assessment, and how instructors set expectations for appropriate use [33]. At the interface level, LLM-based assistants are increasingly framed as mixed-initiative tools that should maintain students' responsibility for sense-making by supporting active engagement and metacognitive monitoring, while also addressing trust, transparency, and user control [19]. These considerations inform the design of AI query interfaces that support ease of use, as well as students' active (meta)cognitive engagement and agency. However, research has been limited in examining how bodily action, spatial navigation, and multimodal interaction can support learning abstract computational concepts for *all* learners.

Interaction Design and Embodied Learning in Immersive XR Learning Environments. Embodied learning theories posit that cognition is grounded in bodily action, perception, and interaction with the environment, emphasizing how movement and sensorimotor engagement shape understanding [16]. HCI has played a central role in translating these theoretical insights into concrete design practices by investigating how bodily action can be deliberately shaped through interaction design [30, 22]. Through work on tangible interfaces, spatial interaction, and whole-body engagement, HCI research has shown how interfaces actively mediate cognition by structuring how users act upon and experience computational representations [21]. XR technologies build on this tradition by enabling immersive environments in which bodily movement and spatial interaction are integral to engagement [21]. Designing such interactions, however, is inherently challenging: embodied actions must be carefully orchestrated to support sensemaking without introducing unnecessary cognitive or physical burden. These challenges intensify in domains such as CS, where abstract and temporally structured concepts resist direct physical mapping, and become even more complex when AI-mediated feedback and adaptive behavior are introduced [37].

3 Methods

This work is grounded in a "Research *through* Design (*RtD*)" methodological stance [41]. Our goal was to surface recurring design tensions as wicked problems [5], offer provocations [37, 2], and articulate design knowledge and orientations for the emerging design space of AI-augmented embodied learning in XR for CS education. Following RtD practices [2], we started a targeted literature review to identify key challenges and opportunities for XR-based learning. We then developed and iteratively refined XR learning concepts that address foundational algorithmic topics such as sorting, loops, recursion, and data structure, supported by large language model-supported design endeavors for initial prototyping . Throughout this process, we sought insights from nine experts and students in CS, education, and visualization. We also presented this work to an experienced local school district leader in technology education. Drawing on these conversations and sessions, we iteratively revised design conjectures and consolidated the articulation of surfaced wicked problems, design knowledge, and orientations. In design and meeting documents, we identified design rationale, moments of breakdown, and unresolved challenges encountered when aligning embodied interaction, AI systems, and algorithmic learning objectives.

This synthesis reflects a reflective and selective account of our design and research experiences, providing a conceptual contribution that offers structure and orientation for future empirical and design-oriented work, while highlighting emerging contributions to the design space. Though we sought input from experts, practitioners, and students, we acknowledge the inherent limitations of our approach and the conceptual nature of this work. Our experiences, with backgrounds in HCI, CS, and Education, have shaped the design process and identification of wicked problems, provocations, and design orientations. This work is intended as an initial contribution to spark further research and exploration in this emerging area.

4 Wicked Problems and Provocations

4.1 Problem and Provocation 1: Epistemic *Mis*match Between Embodied Learning and Abstract CS Concepts

A fundamental wicked problem in designing AI-augmented XR learning environments for CS education is the complex alignment between embodied interaction and the abstract, algorithmic nature of CS knowledge [6]. CS education is concerned with learning specific representations [13], as well as cultivating an algorithmic way of thinking, such as procedural reasoning, abstraction, and temporal control structures. While embodied interactions leverage familiar physical analogies, tasks like programming involve "abstract behaviors" not amenable to direct manipulation [28]. In other words, a student might enthusiastically act out a sorting algorithm with tangible objects, but still struggle to grasp the underlying abstract logic. Embodied learning approaches introduce bodily action and spatial experience as mediating resources for understanding. In XR, embodiment functions as a *designed intermediation* that translates abstract computational structures into experiential forms [34]. However, bodily engagement in XR alone does not guarantee understanding of the concept [18]. The difficulty is not whether embodiment can help, but what the embodiment makes salient. Embodied representations can support explanation and memory while remaining metaphorical or partial, which can constrain transfer to formal reasoning [29].

These tensions are intensified in AI-augmented XR environments. AI systems dynamically adapt representations and guide interaction, yet operate on abstract computational models that are often opaque to learners. When AI-mediated feedback is delivered through embodied interfaces, misalignments can arise between learners' actions, spatial representations, and underlying algorithmic logic of CS concepts. The design challenge, therefore, is to design intermediation that supports algorithmic ways of thinking without obscuring formal structure.

Provocation. How might embodied interaction in XR support algorithmic thinking without collapsing abstract computational structures into misleading physical metaphors—particularly when adaptive AI systems mediate those interactions?

Emerging Design Orientations. AI-augmented XR learning environments should treat embodiment as partial and reflexive rather than complete or "natural." In practice, designers can pair embodied interaction with symbolic and temporal representations that allow learners to transition between experiential and formal reasoning. As such, AI can prompt learners to reflect on discrepancies between intuitive action and algorithmic logic to support more robust and transferable understanding. For example, by mapping abstract CS operations onto intuitive physical metaphors (e.g. walking along a path to trace a loop), these designs reduce the epistemic gap between doing and thinking [40].

4.2 Problem and Provocation 2: Cognitive Load in Embodied XR Learning

Efforts to support abstract CS learning through embodied interaction bring a closely related challenge: managing cognitive load as a consequence of interaction design [31]. Embodied approaches can reduce extraneous load by distributing cognition across bodily action and the environment, allowing learners to externalize representations and offload mental simulation [4]. Purposeful bodily movement aligned with conceptual structure can enhance understanding and retention for abstract domains [26] by increasing germane cognitive load.

XR environments support immersive spatial interaction, making otherwise invisible processes experientially accessible [16, 30]. Yet they introduce new demands: spatial navigation, gesture or controller mappings, multimodal input, and sustained attention. AI-driven feedback adds interpretation and integration tasks. When embodied interaction is conceptually aligned and interaction complexity is well regulated, XR can support algorithmic reasoning by reducing extraneous demands. Excessive or poorly timed AI feedback can amplify intrinsic complexity and introduce additional sensory, motor, and interpretive burdens, causing learners to focus on managing the system rather than developing transferable computational understanding [10]. For example, in a bubble-sorting XR environment (Fig. 1), learners must coordinate hand gestures, spatial attention, visual cues, and AI feedback while reasoning about algorithmic steps. Learning in XR can overwhelm students with sensory richness, interactivity, and novelty—all on top of the domain content itself, risking cognitive overload. Studies of classroom AR, for instance, report that while students appreciate the interactive novelty, many "encountered challenges in sustaining concentration because of the excessively stimulating nature" of augmented environments [32]. Cognitive overload in embodied XR is therefore not inherent, but a consequence of design choices.

Provocation. What if immersive embodiment and AI assistance amplify cognitive burden? Under what conditions does embodied interaction in XR genuinely offload cognitive demands in CS learning, and when does it instead overwhelm learners with sensory, motor, and interpretive complexity?

Emerging Design Orientations. Cognitive load as an integral design issue in AI-augmented embodied XR learning environments. Designers should carefully consider when embodiment enhances conceptual reasoning, how to regulate interaction complexity, and how AI systems can adapt the timing and modality of feedback with real-time data analytics. Visualizations such as intuitive and dynamic natural metaphors [38] may facilitate learning.

4.3 Problem and Provocation 3: Learner-Agent Interaction in XR with AI Feedback Systems and Design

CS education seeks to cultivate algorithmic ways of thinking and reasoning [13]. In XR, these forms of reasoning are mediated through embodied and spatial

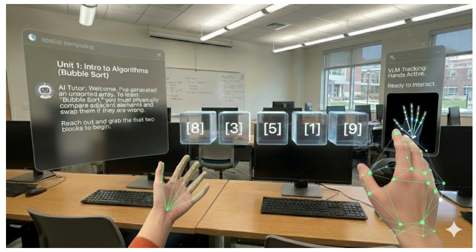

Fig. 1. Large language model (LLM)-supported (i.e., Google Gemini) initial prototyping of the system.

interaction, while AI systems provide adaptive feedback and guidance by interpreting learner behavior [3, 36]. This combination introduces challenges for how learners relate action, feedback, and underlying algorithmic processes.

Adaptive feedback can support learning when timely and contextually appropriate [27, 7], yet excessive guidance may also sacrifice opportunities for constructive struggle that may facilitate sense-making [8]. In embodied XR settings, this tension is intensified: while bodily action positions learners as active agents, AI systems may intervene by interpreting gestures or navigation as indicators of understanding, dynamically reshaping the environment. Such interventions risk shifting learners from sense-makers to responders to system-driven cues.

In a free-form sandbox or game-like XR lesson, where learners take divergent paths, it can be difficult for the system to identify who is struggling and when. Prior approaches that compare student behavior to a single path fall short when many valid solution strategies exist. Yet importantly, such openness can be beneficial since the openness showed higher learning gains for students who explored more, even if they experienced some frustration, as opposed to those who strictly followed a prescribed path [24].

From an HCI perspective, human–AI interaction research emphasizes the importance of intelligibility and negotiability for maintaining user agency and trust [10], due to its concerns around automation and agency. In XR, AI feedback is often spatial, multimodal, and temporally dynamic, making its operation less transparent and harder to interpret [39]. When AI mediation obscures its interpretive logic, misalignments can arise between learner action, system inference, and intended conceptual understanding.

Provocation. How can AI-mediated feedback in XR support algorithmic sense-making by remaining intelligible and temporally aligned with embodied action, without undermining productive struggle or learner agency?

Emerging Design Orientations. AI-augmented XR systems could experiment the interpretive role of AI feedback, making it negotiable and visible, supporting reflection and transitions between embodied interaction and symbolic representations, while preserving learners' responsibility for algorithmic reasoning [38].

4.4 Problem and Provocation 4: Scalable and Accessible Spatial Interactions and System Design in XR

XR learning environments often foreground immersive, individually centered interaction, whereas CS education is commonly conducted in shared and collaborative contexts, including classrooms, labs, and remote or hybrid settings [15]. On a practical level, many educators acknowledge XR's potential but hesitate to adopt it due to lack of training, difficulties with classroom management, and uncertainty about how to fit spatial experiences into an existing curriculum [32]. This creates a persistent design tension: embodied XR experiences that are compelling at the individual level may be difficult to scale or sustain across real educational contexts.

In AI-augmented XR systems, AI promises scalability through automated and adaptive feedback, yet learners may participate through heterogeneous modalities, including VR, XR, desktop interfaces, or observational roles. When spatial interaction and embodiment are central to understanding algorithmic structures, maintaining conceptual coherence across these modes becomes challenging. Differences in immersion, input, and visibility risk producing uneven access to core learning concepts beyond merely varied interaction styles [23, 12]. Immersive systems can privilege particular bodies, devices, and environments, introducing accessibility challenges related to physical ability, sensory access, and institutional resources [11]. From spatial audio cues and haptic feedback for blind users to one-finger VR controllers for learners with limited mobility, XR learning systems can incorporate accessibility-focused interaction techniques [20]. However, these innovations are not yet mainstream, and platform constraints and participation roles remain tightly connected with scalability and accessibility.

Provocation. How can AI-augmented XR learning environments support embodied approaches to algorithmic learning while remaining scalable and accessible across a variety of platforms?

Emerging Design Orientations. Designers might consider balancing conceptual continuity and interactional uniformity, supporting layered participation through adaptable representations, alternative inputs, and shared views that preserve pedagogical coherence across modalities [23].

4.5 Problem and Provocation 5: Designing 3D User Interfaces (UIs) for CS Education in XR Environments

Challenges intensify when spatial arrangements carry semantic meaning, such as tree hierarchies, data pipelines, or neural network layers, where navigation choices affect conceptual understanding, 3D UI design heavily impacts its pedagogy. Poorly designed interfaces can produce spatial confusion, mode-switching errors, or accessibility barriers, including motion sickness or physical limitations [30, 9]. Cross-reality contexts further complicate design. 3D UI design effective in VR may not transfer to AR, yet coherence across platforms is crucial for accessible learning experiences. Early explorations are promising: block-based programming in VR maintained students' programming performance on par with

a standard desktop interface, even though it required physical movement and spatial interactions [14]. However, designing 3D UIs still demands careful consideration of human factors. Issues like spatial layout of code, discoverability of functions, precision of gestural input, and potential fatigue all come into play.
Provocation. How might XR interfaces allow learners to manipulate computational concepts directly without being burdened by interface complexity? Could pedagogical intent be embedded into navigation mechanics, or could AI dynamically adjust interaction complexity based on learner expertise? Do such designs reduce cognitive load and enhance conceptual understanding, or risk creating opaque or agency-reducing experiences?
Emerging Design Orientations. Designers might explore "invisible" interfaces where navigation and manipulation are guided by AI while preserving learner agency, embed pedagogical affordances into embodied mechanics, and scaffold interaction complexity adaptively. For example, by linking code elements to physical locations (e.g. placing a "if motion sensor triggers" block on the virtual door in the scene), the UI externalizes the program flow into the 3D world [17]. This spatial contextualization helps students form mental models "at a familiar level of abstraction" connecting code with real-world referents.

5 Discussion and Implications

In this paper, through *RtD* [41], we identified key challenges and provocations for designing AI-augmented, embodied learning experiences in XR for CS education. We propose *five* "wicked problems" [5] and emerging design orientations, accompanied by provocations [2] to guide future design and research in this area. These ideas are interconnected, offering a cohesive account for exploring this under-theorized design space.

Positioned as an initial contribution to the design space for HCI research, these wicked problems, design orientations and provocations surfaced how the interactions between disciplinary concepts, technological affordances and constraints, and learner experience design can influence the overall design of educational tools. These design issues add to the ongoing discussions on the complexities of designing AI technologies [37], automated learning feedback systems [27, 15, 3, 10], and XR environments [1, 36]. Building on the discussed design issues, this study derived three design and research implications. First, our provocations call for an ontological framing of CS concepts as they are enacted through embodied learning in XR environments. We argue that designers' ontological framing is a critical component of interaction design in shaping the alignment, or misalignment between experiential learning and abstract computational concepts. Such framing shapes users' and learners' computational experiences, influences how embodied actions are interpreted, and structures how algorithmic modes of expression are made sense of within AI-augmented XR systems. Second, our study also highlighted issues related to designing learner interactions in conjunction with cognitive load and learner agency. User interface design concerns how to present information in the most manageable ways, aligning with learners' bodily movements. Designers could experiment with the timing, location, and quantity of information and feedback delivered to the learners, optimizing these factors to reduce cognitive load and enhance engagement. Finally, situating the design within XR enables designers to explore ways to ensure that AI-augmented systems are scalable, adaptable, and accessible across a wide range of educational contexts and learner needs.

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