An Embodied Learning System in AI-Supported Mixed Reality for Computer Science Education

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Abstract. Abstract concepts in computer science (CS) education, particularly in computer organization and architecture, are often difficult for learners to internalize using traditional instructional materials such as textbooks or static diagrams. These topics require the formation of dynamic mental models, which many students struggle to construct through traditional learning methods alone. To address this challenge, we present ECLIPSE (Embodied Cognition and Learning in AI-supported Platform for Computer Science Education), a Mixed Reality (MR) learning environment that leverages large language models (LLMs) and vision-language models (VLMs) to create adaptive, spatially grounded representations of abstract computing concepts. Grounded in embodied cognition theory and constructivist pedagogy, ECLIPSE enables learners to physically interact with and navigate through concepts such as bubble sort and cache memory, receiving real-time, AI-driven feedback. This interactive, discovery-based approach aims to deepen conceptual understanding by linking physical experience with abstract reasoning. In this workshop paper, we outline the system overview, including the design rationale, and current progress, containing paper prototyping, web-based prototyping, and participatory co-design sessions. We conclude by discussing broader implications for the design of AI-supported mixed reality environments in CS education.

Keywords: Artificial intelligence · Embodied cognition · Mixed Reality.

1 Introduction

Foundational concepts in computer science—algorithms, data structures, memory hierarchies—are inherently abstract, yet they form the bedrock of computer science (CS) education [6]. Learners typically encounter these ideas through code listings and static diagrams, affording little opportunity to build the kind of intuitive, spatial understanding that experienced practitioners develop over years [7]. Research in cognitive science consistently shows that embodied, action-based engagement with material can support meaningful mental-model construction [2, 4] and hence portrayed potential to enhance learning in computer science learning.

Extended Reality (XR) technologies offer a compelling substrate for making these abstractions tangible. Mixed Reality (MR) in particular preserves the learner's physical environment while layering interactive 3D representations onto it, supporting agency and presence unavailable in conventional learning tools. Simultaneously, large language models (LLMs) and vision-language models (VLMs) have matured over time to serve as real-time learning agents, interpreting learner actions, diagnosing misconceptions, and generating contextually grounded learning guidance.

We present *ECLIPSE* (*Embodied Cognition and Learning in AI-supported Platform for Computer Science Education*), an MR system targeting CS education for adolescents and young adults. Starting with bubble sort and cache memory hierarchy, two concepts simultaneously foundational and notoriously hard to master, ECLIPSE maps each concept onto a navigable spatial metaphor and wraps it in an adaptive AI feedback loop. This paper describes the system's design rationale, current design and implementation states, and implications for AI-supported immersive learning.

2 Related Work

Embodied cognition theory posits that cognitive processes are grounded in the body's sensorimotor interactions with the environment [2, 4]. In educational contexts, embodied activities have been shown to support the development of intuitions that transfer to formal symbolic tasks [4]. Prior work such as CS Unplugged [9] demonstrates that physically enacting algorithms can foster computational thinking before learners engage with code [8]. ECLIPSE extends this approach into mixed reality (MR), where physical enactments are augmented with real-time AI-driven feedback [5]. Additionally, research has shown that 3D visualizations of program execution can reduce cognitive load and improve debugging performance [3]. In immersive learning environments, studies highlight that digital overlays anchored to physical space enable learners to leverage spatial memory more effectively [10]. On the AI side, intelligent agents in learning systems have demonstrated advantages over traditional approaches, while recent integration of large language models (LLMs) has enabled more open-ended and adaptive dialogue [1]. Vision-language models (VLMs) further extend these capabilities by allowing systems to perceive and reason about learners' spatial interactions—an approach central to the design of ECLIPSE.

3 System Overview: ECLIPSE

3.1 Design Rationale

Three theoretical foundations underpin ECLIPSE's design. First, spatial anchoring: each CS concept is mapped to a navigable physical metaphor. For example, in the bubble sort module, data elements appear as floating blocks of varying heights inside a "sorting arena," and learners sort them using only adjacent-swap gestures, mirroring the algorithm's constraints. In the cache memory module, learners interact with a structured space of "gates" representing different levels of memory access. They activate and navigate these gates to execute data flow operations and observe differences in how information is retrieved, supporting an intuitive understanding of memory hierarchy and locality. This spatial grounding is intended to support the formation of mental models similar to those used by experts when reasoning about algorithmic efficiency and data access. Second, adaptive AI scaffolding: a persistent learning companion agent assuming mixed roles to monitor learner actions through a VLM pipeline and generates context-sensitive hints and Socratic questions. The LLM maintains a lightweight learner model, including per-concept mastery estimates, misconception indicators, and interaction history, and applies faded scaffolding by gradually reducing support as competence increases. Third, learner-centered iterative design: ECLIPSE has been co-developed with CS students and instructors through a participatory design process, ensuring that spatial metaphors and interaction patterns are both interpretable and pedagogically meaningful prior to full hardware deployment.

3.2 Current Progress

ECLIPSE has progressed through two prototyping stages. In the paper prototyping stage (n = 11 stakeholders), participants enacted sorting arena and cache navigation scenarios using physical props. This stage validated the core spatial metaphors and revealed critical scope and design tensions. Specifically, it helped define the target abstract concepts and highlighted trade-offs between visualization design and the facilitation of embodied learning experiences.

Digital web-based prototyping sessions (n = 7 CS undergraduate and instructor participants) were conducted to further explore and refine the design directions emerging from the paper prototyping stage. Rather than directly addressing previously identified issues, these sessions provided support for earlier design decisions and offered insight into participants' meaning-making processes and reflections on concepts encountered in their CS coursework. During the sessions, participants first articulated their reasoning about how data would flow through the system, and then tested these hypotheses by interacting with "gates" within the functional prototype. This process revealed how learners iteratively connect prior knowledge with interactive representations. Participants also reflected on their learning experiences, noting how the system aligned with or extended their existing understanding. Additionally, participants also suggested that microarchitecture concepts would be particularly well-suited for inclusion in an MR learning environment.

The AI backend currently supports interaction analysis and provides real-time, hint-based feedback. This design is intended to expand by incorporating VLMs to interpret interface frames of learners' hand positions and interactions, alongside LLMs for adaptive learning support. Immediate next steps include full headset integration and usability studies in subsequent development cycles.

4 Discussion and Future Work

ECLIPSE is motivated by the challenge that many core CS abstract concepts require extensive experience to develop robust mental models, particularly those involving algorithmic behavior and memory systems. The system explores how embodied interaction in MR, combined with AI-driven scaffolding and human activity recognition, can support the development of these mental models in a more immediate and intuitive way. By situating abstract concepts in spatially grounded environments, learners engage with ideas through perception and action in addition to purely symbolic representation. The integration of LLMs and VLMs enables adaptive feedback that responds to learner behavior in real time, supporting reflection during interaction. Future work will focus on design-based development of the learning environments and expanding the range of CS concepts represented in embodied MR environments.

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