Embodied AI and Adaptive Cognitive Offloading: Future Challenges for Human-Robot Collaboration

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Abstract

Cognitive offloading, defined as the delegation of cognitive operations to external resources (McDonald et al., 2011; Risko & Gilbert, 2016), has become a key concept for understanding how humans interact with technological tools. This phenomenon reflects a broader theoretical shift in cognitive science, as captured by the 4E framework, which encompasses extended, embodied, enactive, and embedded cognition. The 4E model seminally proposes that cognitive processes are not solely restricted to the brain but are deeply rooted in, shaped by, and constituted by the entire body and its interactions with the environment (Clark & Chalmers, 1998; Newen et al., 2018; Varela et al., 1991).

However, recent developments in AI and robotics introduce systems that go beyond passive cognitive tools. Unlike traditional external aids, embodied AI can actively interact with humans and their task environments during cognitive processing (Rivera-Novoa & Duarte Arias, 2025), enabling artificial agents with physical bodies to learn from interactions with their surroundings (Duan et al., 2022; Liu et al., 2025; Yifan et al., 2025). Through this interaction, robotic systems may serve as external cognitive resources that support the offloading of specific cognitive processes (Laschi, 2025). Paradigmatic examples include collaborative robots assisting navigation in unfamiliar or high-risk environments and assistive robots used during medical procedures, where perceptual, memory, and decision-making demands are partially delegated to embodied AI agents. Therefore, embodied AI systems enable interactive cognitive offloading, in which cognitive demands are dynamically redistributed between human and artificial agents during task execution.

From a theoretical perspective, this redistribution suggests that cognition may be understood as dynamically distributed across hybrid human-AI embodied systems rather than confined to an individual mind (Hutchins, 1995; Sidji et al., 2025). However, the implications of this redistribution remain to be clarified. While cognitive offloading can enhance immediate

performance and reduce internal demands, it may also be a threat for users' cognitive abilities due to excessive reliance on external supports (Grinschgl & Neubauer, 2022). In the case of embodied AI, this issue becomes more complex, since cognition is not merely externalized to a passive tool but continuously reshaped through interaction with artificial agents during task execution. These developments raise deeper questions about the boundaries of human cognition and about how the cognitive sense of self may be reshaped in hybrid human-AI systems. As presciently anticipated (Clark, 2001), the new millennium should radically reconfigure our image of human cognition within the cognitive sciences, integrating embodied, distributed, and enacted cognition with robotics and AI.

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