

Ask the Experts: Co-Designing Adaptive XR Training for Challenging Environments

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Abstract

Training in safety-critical environments requires embodied, sensorimotor competencies that are difficult or dangerous to develop through real-world exposure alone. Extended reality offers a promising medium for such training, with visual fidelity often treated as a key foundation. We argue, however, that an important step comes before optimizing fidelity: identifying, together with domain experts, which conditions actually need to be simulated. We highlight how experts contribute tacit knowledge about physical, environmental, and contextual conditions that task analysis alone may not capture. This knowledge can determine which aspects of the real environment to represent and which fidelity dimensions to use. We therefore position co-design as a foundational step in XR training design, making environmental, collaboration, and hazard conditions explicit, adjustable dimensions for adaptive training.

Keywords

extended reality, challenging environments, expert co-design, visual fidelity, interaction fidelity

1. Introduction

Training in challenging environments carries consequences that training in other domains does not. A pharmaceutical technician who mishandles a syringe in a cleanroom risks contaminating an entire production batch. A wind turbine technician caught unprepared in a nacelle during a storm faces life-threatening conditions several meters above the ground. A theater evacuation coordinator who has never experienced emergency chaos risks failing the hundreds of people in their care. In each of these cases, training is not merely about acquiring knowledge. It is about building the embodied and sensorimotor competencies needed to act correctly under pressure, in conditions that are difficult, dangerous, or simply unfeasible to rehearse in the real world.

Extended Reality (XR) has emerged as a promising medium for exactly this kind of training. By simulating environments that are hazardous, inaccessible, or prohibitively expensive to replicate, XR enables safe, repeatable exposure to high-stakes conditions [1]. Research in XR for critical and challenging environments has grown accordingly, spanning domains from surgical training [2] to industrial maintenance [3, 4] to emergency response [5]. Much of this work places strong emphasis on visual fidelity, that is, how closely the rendered environment resembles the real one. This is a reasonable starting point: visual realism helps make a simulated environment recognizable and credible.

We argue, however, that visual fidelity alone is insufficient. The conditions that make critical environments difficult are often not primarily visual. They may involve the physical resistance of equipment, the motion of unstable platforms, intense noise, spatial disorientation, or the cognitive demands of operating under pressure. These conditions are haptic, proprioceptive, auditory, and cognitive. A training system may reproduce a cleanroom in photorealistic detail yet fail to simulate the resistance of malfunctioning equipment. Likewise, a nacelle may look accurate while omitting the sway and noise associated with extreme weather. In both cases, the simulation may appear realistic while missing the conditions that matter most for trainee preparation. This points to a broader way of thinking about fidelity.

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Importantly, these non-visual dimensions are not only relevant to realism. They also define what an adaptive training system can manipulate. Prior work has shown that training conditions such as task difficulty, scaffolding, feedback modality, and scenario complexity can be adjusted in response to the learner’s state [6, 7, 8]. Multimodal sensing can also inform such adaptation, including physiological measures associated with stress, cognitive load, and engagement [8, 9]. But adaptive systems can respond only to what they can sense, and they can adjust only what has been designed to be adjustable. If important conditions such as resistance, motion, or sensory intensity are absent from the simulation, neither sensing nor adaptive logic can introduce them after the fact. Identifying the relevant fidelity dimensions is therefore not only about realism, but also about determining which aspects of the training environment can be meaningfully adapted to individual trainees. Here, we argue that domain experts play a central role in identifying which conditions should be represented and, importantly, which can become adjustable dimensions of adaptive XR training. We particularly highlight how expert-identified conditions can inform controllable fidelity dimensions, providing a foundation for sensing-informed adaptation and progressive training.

2. The Role of Co-Design in Highlighting What Must Be Simulated

The opportunity we describe is also methodological. XR training systems are often designed around what can be modeled, rendered, tracked, or otherwise reproduced technically. Less often foregrounded is the knowledge domain experts have about conditions that are difficult to observe or infer. In critical environments, much of this knowledge is tacit: it may not appear in manuals, site photographs, or formal task analyses, but instead comes from repeated experience of how the environment behaves in practice. Such knowledge is often contextual and embodied, and may only become explicit when experts can point to relevant features in situ. Co-design is a well-established approach in human-computer interaction (HCI) and has been explored in various XR applications, such as rehabilitation [10, 11, 12] and human-robot interaction [13, 14]. In this work, we focus on its role in identifying domain conditions that can inform controllable fidelity dimensions for XR training.

Co-design offers a way to access this knowledge [15]. By involving domain experts as active participants in the design process, rather than only as validators of an already built system, researchers can identify requirements that might otherwise remain invisible [16]. Importantly, these requirements can inform not only what needs to be simulated, but also which conditions should be adjustable as trainees progress. In critical environments, where overlooking an important condition may directly affect training validity, expert knowledge should therefore be treated as a design input from the outset.

Through on-site visits, interviews, and ongoing discussions with practitioners across three domains, cleanroom pharmaceutical manufacturing, wind turbine maintenance, and theater emergency evacuation, we encountered conditions that would have been difficult to identify through literature review or remote needs assessment alone. For instance, while wind turbine experts were less concerned with the realism of the proposed ladder-climbing interactions, they strongly emphasized the importance of simulating nacelle movement and environmental cues such as wind. Similarly, pharmaceutical cleanroom experts demonstrated specific procedures, potential failures, and the corresponding corrective actions. In theater emergency evacuation, discussions with experts revealed that challenges arise across backstage, stage, and audience seating areas. Moreover, assigning and communicating evacuation responsibilities emerged as a persistent challenge, particularly when managing panicking crowds. These examples highlight how collaborating with domain experts can challenge researchers’ initial assumptions and reveal conditions that may otherwise be overlooked when designing XR training systems.

3. Towards Adaptive Training in Critical Environments

A richer set of fidelity dimensions does not necessarily make training more overwhelming. Instead, it can make training more precise. This precision depends on grounding visual and interaction fidelity

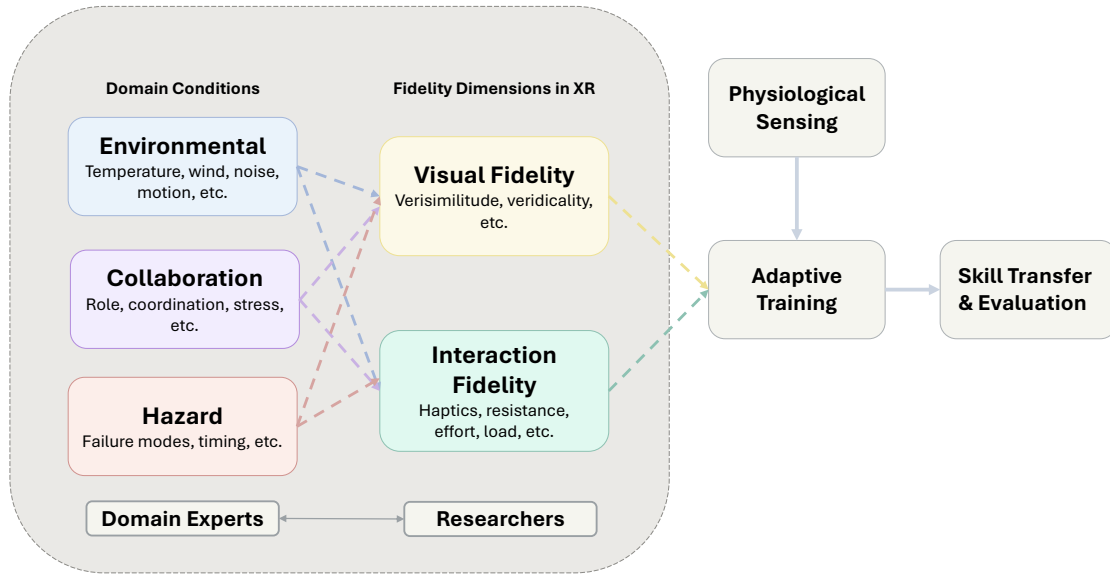


Figure 1: Co-design between domain experts and researchers helps identify the environmental, collaboration, and hazard conditions that should be represented in XR training. These conditions inform the relevant visual and interaction fidelity dimensions, which, together with physiological sensing, provide a foundation for adaptive training and, ultimately, skill transfer.

in the conditions that experts identify as consequential: environmental factors that alter perception, collaboration demands that shape behavior, and hazard conditions that determine what can go wrong. Co-design gives these fidelity dimensions their content, as illustrated in Figure 1. Without it, a simulation may be visually convincing and interactionally rich, yet still fail to prepare trainees for the conditions that matter most.

Once these conditions are represented explicitly, they can also become adjustable dimensions of the training experience. Environmental stressors, interaction demands, collaboration complexity, and hazard severity can be introduced gradually and tuned as the trainee develops. A novice technician, for example, might begin training in a cleanroom under stable conditions, with predictable equipment behavior and little time pressure. As competence develops, equipment failures, environmental stressors, or coordination demands can be introduced progressively. Training can therefore increase in difficulty in a controlled manner rather than exposing trainees to the full complexity of the task from the outset. Similarly, the wind turbine experts' emphasis on nacelle movement and wind-related environmental cues could inform the design of adjustable training conditions, such as simulated movement intensity and wind noise. These conditions could be introduced progressively, allowing trainees to experience increasingly challenging environmental demands. In theater emergency evacuation, the challenges associated with assigning and communicating responsibilities could inform adaptive scenarios with varying crowd sizes and behaviors, coordination demands, and levels of urgency. Such conditions could be adjusted to progressively challenge trainees' decision-making and collaboration skills.

Physiological and behavioral sensing can make this progression responsive rather than purely predetermined. When the simulation represents relevant task demands, signals such as heart rate variability, pupil dilation, and movement behavior can be interpreted alongside changes in the training environment. These signals may help indicate when a trainee is experiencing increasing cognitive or physical strain, allowing the system to adapt individual training dimensions accordingly. Importantly, such adaptation depends on those dimensions being represented and controllable in the first place.

4. Conclusion

To that end, we argue for expanding the design space of XR training by connecting domain experts' knowledge with adaptive training requirements. Before optimizing visual or interaction fidelity, researchers need to identify which conditions matter, which aspects of those conditions should be simulated, and how they should be represented. Through co-design, these conditions can be translated into controllable fidelity dimensions that provide meaningful targets for sensing-informed adaptation and progressive training. This brings XR training closer to what critical environments require: realistic, challenging experiences that remain controlled, safe, and responsive to the individual trainee.

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Declaration on Generative AI

During the preparation of this work, the author(s) used Claude.ai for grammar and spelling checks and content refinement. After using these tool(s)/service(s), the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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