Differentiating XR Modes to Study Pedestrian Behaviour during Fire Evacuations

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Abstract This study systematically evaluates Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), to assess their effectiveness in simulating fire evacuations. Sixty-one participants completed evacuation tasks across four reality modes, including Physical Reality (PR), while their movement patterns, biometric signals, and subjective responses were recorded. This study examines differences in psychophysiological, tactical, and operational behaviours across XR modes in fire evacuations, with emphasis on their ecological validity.

Keywords XR, VR, AR, MR, Fire, Evacuation, Tactical, Operational, Pedestrian behaviour

Introduction

Understanding how individuals navigate fire evacuations is essential for improving emergency protocols and the safety of the built environment. Replicating such dangerous conditions in real-world settings poses significant ethical and safety concerns, making traditional pedestrian study methods impractical for analysing these behaviours [1]. However, fire hazards impose time-sensitive, high-risk decision-making demands, making it crucial to investigate tactical, operational, psychological, and physiological responses. Although VR has been extensively used to replicate hazards, concerns remain regarding ecological validity [2], navigation fidelity, and simulation sickness [4]. AR and MR introduce virtual fire hazards within real-world spaces, potentially enhancing behavioral realism [3]. This study evaluates VR, AR, MR, and PR to determine their ecological validity and effectiveness in simulating fire evacuations.

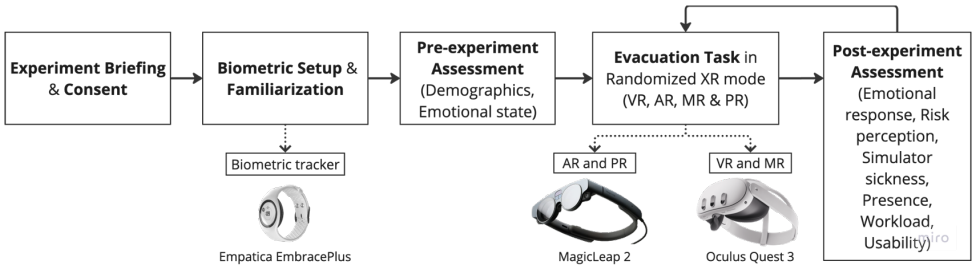

Figure 1: Schematic representation of the experimental procedure

Experimental Design and Setup

A G*Power analysis ($|\rho| = 0.25$, $\alpha = 0.05$, power $= 0.95$) determined a minimum required sample size of 44. To enhance statistical robustness, 61 participants (aged 18–50) were recruited, balanced between those familiar and unfamiliar with the environment.

The experiment followed a structured five-stage process: (1) briefing and consent, (2) biometric setup and familiarisation, (3) pre-experiment assessment, (4) four randomised evacuation tasks across XR modes (VR, AR, MR) and PR, ensuring equal distribution of XR modes as the initial task, and (5) post-experiment assessment. Biometric data were recorded using the Empatica EmbracePlus wristband, while XR evacuations were conducted using the Magic Leap 2 (AR, PR) and the Quest 3 (VR, MR). Tactical, operational, physiological, and subjective responses were recorded. To maintain consistency, all XR environments were developed in Unity 3D using identical 3D assets, visual settings, and audio cues.

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The evacuations took place in the sixth-floor common area of TU Delft's Civil Engineering building. AR and MR conditions projected a simulated fire hazard into real-world space via Magic Leap 2 and Oculus Quest 3. The VR condition fully reconstructed the environment within Oculus Quest 3. The PR evacuation task (baseline) involved a real-life evacuation under a fire alarm without any simulated visuals using Magic Leap 2 headset to standardise data collection, ensuring consistency in sensory input across conditions.

Experiment Procedure and Data Collection

Ethical approval for the study was granted by the Human Research Ethics Committee (HREC) of the Delft University of Technology. Figure 1 outlines the experiment procedure, which lasted between 30 and 50 minutes per participant. During the experiment, positional tracking and physiological data were recorded, including evacuation time, route choice, exit selection, and obstacle collisions.

Physiological data, such as blood volume pulse (BVP), electrodermal activity (EDA), and wrist temperature, were recorded using the Empatica EmbracePlus wristband. Subjective measures were assessed through validated questionnaires evaluating risk perception, affective state, presence, simulation sickness, workload, and usability. To enhance validity, all experimental conditions were conducted under similar ambient lighting, temperature, and noise levels to mitigate confounding variables. Each session concluded with an open-ended debriefing to gather qualitative insights into the user experience.

Figure 2 presents biometric data from the Empatica EmbracePlus across all four tasks, illustrating trends in EDA, temperature, and BVP. Figure 3 visualises XZ evacuation trajectories, highlighting navigational differences among XR conditions for a pilot participant. Initial pilots reveal clear circumvention behaviour in XR-induced fire settings and significant trajectory deviations in PR, suggesting differences in hazard perception and route choices.

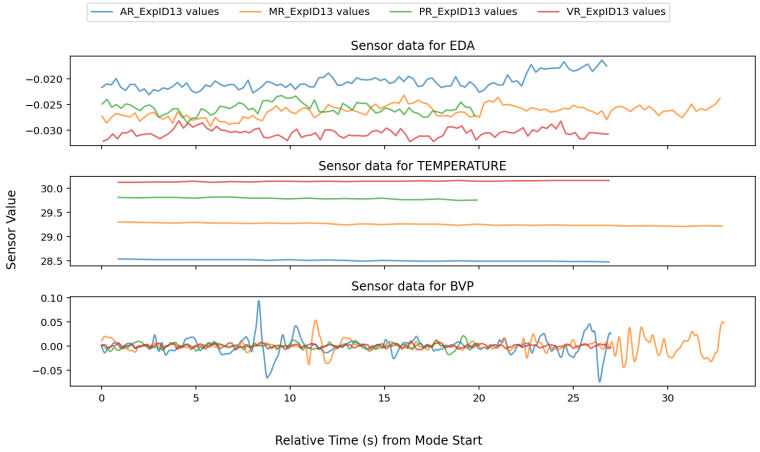

Figure 2: Empatica's biometrics data recorded across four tasks

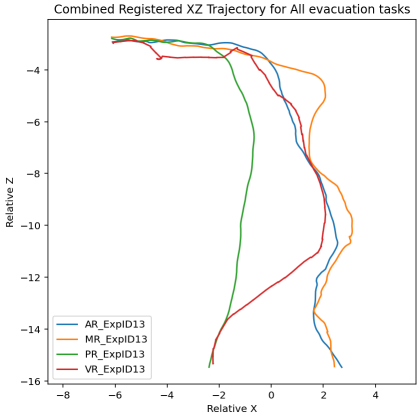

Figure 3: Pilot participant's evacuation trajectories across four tasks

The full paper will further examine how different XR modes replicate real-world evacuation behaviour by analysing spatial decision-making alongside psychological and physiological stress responses. Special emphasis is placed on the ecological validity of XR environments, and their implications for advancing fire evacuation research and safety training.

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