VR-CivicGuard: Enhancing Campus Civil Defense and Air Defense Preparedness through Immersive Virtual Reality Training

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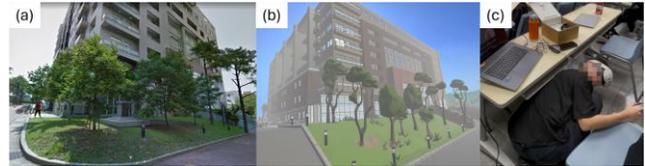
Figure 1. In-game experience of VR-CivicGuard

Figure 2. (a) Real building (Source: Google Street View); (b) Scene reconstruction in our system; (c) Participant practicing postures.

ABSTRACT

As drones and missile strikes become major threats in modern warfare, traditional civil defense training often fails to build the procedural memory required for survival. We present VR-CivicGuard, an immersive VR simulation that trains users in expert-informed air raid standard operating procedures. Developed through interviews with civil defense specialists, the system targets critical survival skills, including blast-mitigation posturing, emergency item collection, debris navigation, and drone evasion. A pilot study showed high usability and immersion, and participants trained with VR-CivicGuard significantly outperformed a control group. These findings highlight the effectiveness of expert-informed VR for civil defense training.

Index Terms: Virtual Reality (VR), Emergency Preparedness, Civil Defense Training, 3DGS, Campus Security.

1 INTRODUCTION

While government-led protocols for natural disaster response are well-established, public preparedness for civil defense, specifically wartime scenarios, remains critically underdeveloped. Traditional instructional methods relies on passive media such as videos and brochures, which fails to instill the situational awareness and reflexive physical responses necessary for survival under duress. Air raids, arguably the most probable threat to civilians, require immediate, embodied reactions that passive learning cannot effectively cultivate. To address this gap, we introduce VR-CivicGuard, an immersive Virtual Reality training system designed to enhance civilian air defense preparedness in a campus environment. Unlike prior VR emergency training systems that focus on professional responders or combat-oriented scenarios, our approach targets everyday civilian survival behaviors. Developed in consultation with civil defense experts, the system targets critical survival gaps often overlooked in standard drills, including blast shockwave mitigation, strategic positioning for cover and concealment, and evasion behaviors under hostile drone surveillance (see Fig. 1). Leveraging the affordances of embodied interaction, VR-CivicGuard reconstructs a high-fidelity digital twin of a school building to simulate high-stress air raid scenarios involving sirens and drones. Rather than emphasizing combat engagement, the system focuses on the primary causes of civilian injury such as blast waves and structural fragmentation (e.g., shattering glass). This work details the system's design and provides empirical evidence demonstrating how expert-informed, embodied VR interaction can transform theoretical civil defense knowledge into practical, reflexive survival skills.

2 IMPLEMENTATION AND SCENE DEVELOPMENT

2.1 Hardware and Interaction Framework

The system is built on Unity 6 (URP) for Meta Quest 3. We utilized Meta XR Core SDK to implement 6DoF tracking and hand-gestures. To ensure safety, users remain seated, using controller-based locomotion while physical movement is limited to rotation and crouching within a cleared, obstacle-free space.

2.2 Reference-Based Scene Reconstruction

Following expert-led civil defense requirements, we developed a digital twin of the campus environment (see Fig. 2(b)). 3D Gaussian Splatting (3DGS) [1] was used to process handheld video scans into a high-precision point cloud, which served as a reference for modeling physics-ready geometry in Blender, ensuring that the virtual environment maintains an authentic scale for effective spatial learning.

2.3 Dynamic Event and Hazard Systems

The simulation follows a linear event system with three core scenarios: indoor blast-mitigation, debris navigation, and outdoor drone evasion. To replicate air raid hazards, a Dynamic Mesh Shattering System simulates structural failures, where users in "red zones" (paths of fracturing glass) trigger a "Critical Injury" state to reinforce cover-seeking SOPs, such as sheltering under desks. Navigation is guided by a diegetic NPC (cat) using a Finite State Machine (FSM) and NavMesh to lead users through dynamic debris. For outdoor threats, hostile drones employ a Raycast-based patrol algorithm to detect unoccluded users, mandating strict concealment maneuvers to avoid detection.

2.4 Performance Optimization for Standalone VR

To maintain standalone VR frame rates, we adopted a hybrid lighting strategy: baked lightmaps for static structures and real-time lighting for dynamic hazards. Modular instancing and occlusion culling further minimize draw calls during scene transitions.
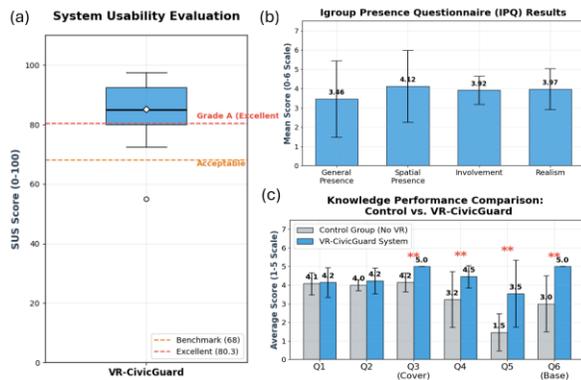
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Figure 3. Evaluation results of VR-CivicGuard: (a) SUS boxplot showing excellent usability (M=85.19); (b) IPQ scores indicating high spatial presence and immersion; (c) Comparison of knowledge performance between the VR and Control groups (p < 0.001).

3 USER STUDY AND EVALUATION

3.1 Participants and Experimental Design

We conducted a between-subjects user study with 26 participants (19 male, 7 female; age M=21.4, SD=2.3) to evaluate the system's effectiveness (see Fig. 2(c)). Participants were randomly assigned to either the VR Group (n=13; 10 males, 3 females) experiencing the full VR-CivicGuard workflow, or the Control Group (n=13; 9 males, 4 females) underwent the assessment relying solely on their prior experiences with conventional disaster preparedness drills, without receiving any additional training.

3.2 Experimental Procedure

The 15-minute experimental protocol consisted of: (1) Pre-study briefing (2 mins) on hardware and SOPs; (2) Immersive Training (10 mins): Participants in the VR group navigated the air raid narrative, performing survival tasks (e.g., finding cover, avoiding glass) guided by the diegetic NPC; and (3) Post-Study Assessment (3 mins) involving questionnaires and a short interview.

3.3 Measurement Instruments

To rigorously evaluate the system's performance and educational impact, we employed four validated instruments: (1) Knowledge Assessment: A 6-item quiz focusing on expert-informed procedural SOPs to measure learning gain; (2) System Usability Scale (SUS) [2]; (3) Igroup Presence Questionnaire (IPQ) [3]; and (4) Simulator Sickness Questionnaire (SSQ) [4].

4 RESULT AND DISCUSSION

4.1 System Usability Scale (SUS)

VR-CivicGuard achieved a mean SUS score of 85.19 (SD = 12.05), indicating "Excellent" usability (see Fig. 3(a)). While the overall feedback was positive, the item "I would need the support of a technical person" received lower scores, suggesting that some users felt uncertain without external guidance. Based on interview feedback, we plan to replace text-based UI with spatial audio cues to provide directional support without visual obstruction.

4.2 Igroup Presence Questionnaire (IPQ)

We employed a modified IPQ to assess user immersion across four dimensions (see Fig. 3(b)). Spatial Presence received the highest rating (M = 4.12, SD = 1.86), confirming that the digital twin of the campus environment and the interaction feedback successfully enhanced environmental awareness. Other metrics, including

General Presence (M = 3.46, SD = 1.98), Involvement (M = 3.92, SD = 0.73), and Realism (M = 3.97, SD = 1.06), remained above the mid-point (3.0), indicating a successful immersive experience.

4.3 Simulator Sickness and Comfort

SSQ results and interview indicated no significant discomfort for most participants. To mitigate reported motion sickness in a minority, we have introduced adjustable movement speeds and disabled non-realistic locomotion (e.g., jumping, snap-turning) to better align the visual flow with real-world physical perception.

4.4 Knowledge Acquisition and Statistical Analysis

An independent samples t-test (see Fig. 3(c)) showed the VR Group (M = 87.95%, SD = 8.01) significantly outperformed Control Group (M = 66.41%, SD = 7.56), with p < 0.001, particularly in blast-mitigation postures. Based on these preliminary findings, while VR effectively enhances survival knowledge, future studies will employ a more rigorous "standard media" control group (e.g., printed manuals) to further evaluate VR's comparative efficacy in cognitive load and emotional dynamics, as suggested in recent research [5].

5 CONCLUSION AND FUTURE WORK

VR-CivicGuard demonstrates high usability and effectively bridges the gap between theoretical knowledge and practical air raid survival skills. While the current 3DGS-based workflow relies on manual reconstruction, limiting scalability, future work will integrate real-time spatial scanning with automated physics generation. By developing a pipeline that generates simplified mesh colliders directly from 3DGS scans, we aim to overcome the lack of defined collision boundaries in radiance fields. This breakthrough will enable a "scan-and-train" capability, allowing users to transform immediate real-world environments into customized training scenarios without expert 3D modeling, significantly enhancing the accessibility of civil defense training.

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