From Teaching Specifications to Embodied Interaction: A VR System Translation Framework for K-12 Fire Safety Education

Shiting Jiang

School of Design and Architecture, Zhejiang University of Technology, Hangzhou 310023, China

441745722@qq.com

Abstract. Traditional campus safety education often relies on textual instructions and classroom lectures, which makes it difficult for students to translate abstract knowledge into appropriate actions in real emergency situations. Although virtual reality (VR) has been widely introduced into educational contexts, systematic methods for transforming safety curricula into interactive VR experiences remain limited. This study proposes a text-to-interaction transformation framework for K–12 fire safety education. Fire safety knowledge is decomposed into three hierarchical interaction events: Perception, Judgment, and Action (PDA). Based on this model, a prototype system named FireEscape-VR was developed using the Unity engine. Expert evaluation conducted with three experienced safety education teachers indicates that the PDA framework effectively translates abstract safety regulations into embodied interactive behaviors. The proposed approach provides a reusable design paradigm for developing VR-based safety training systems.

Keywords: Virtual Reality, Interaction Mapping, Embodied Cognition, System Design, K-12 Safety Education.

1 Introduction

1.1 The Knowledge–Action Gap in Safety Education

Fire safety education is a critical component of K–12 curricula, aiming to equip students with essential survival skills in emergencies [1]. However, traditional safety education mainly relies on lectures and manuals that emphasize memorization of safety rules [2]. While these methods can be effective in conveying declarative knowledge, they often fail to support the transformation of abstract knowledge into behavioral competence under stressful conditions [3].

This phenomenon is known as inert knowledge, where learners possess knowledge but fail to apply it in real situations [4]. In actual fire incidents, deficiencies in proce-

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dural memory frequently lead students—despite memorizing safety rules—to make incorrect decisions due to panic [5]. Consequently, safety education needs interactive approaches that bridge abstract knowledge and real-world actions.

1.2 Research Objectives and Contributions

To address this engineering and design challenge, the present study does not focus on quantitatively validating learning outcomes; instead, it concentrates on the design methodology underlying the construction of VR-based educational environments. We propose a text-to-interaction transformation model tailored to K–12 contexts.

Specifically, this study elaborates on how a three-layer mapping architecture—Perception–Judgment–Action—can be employed to translate rigid safety regulations into immersive streams of interactive events. By presenting this systematic design framework, the paper aims to provide future developers of VR educational content with a reusable narrative construction paradigm, thereby enhancing both the engineering quality and user experience of safety education software.

2 Related Works

2.1 VR-Based Safety Education for K–12 Learners

Virtual reality (VR) enables safe simulation of hazardous environments and has been widely explored for safety training. For example, Lovreglio et al. showed that immersive VR simulations can improve procedural learning and situational awareness in fire safety training [2]. Similarly, evacuation simulations indicate that interactive virtual environments support rehearsal of emergency procedures before real-world drills [5].

Beyond evacuation training, VR has also been applied in broader educational contexts. Mayer et al. emphasized that the effectiveness of VR learning largely depends on instructional design rather than the technology itself [9]. Other studies suggest that immersive VR experiences can enhance learning outcomes through emotional engagement and embodied interaction [7].

However, existing research mainly focuses on evaluating learning outcomes, such as knowledge retention, immersion, or behavioral performance. Comparatively fewer studies examine how instructional content can be systematically translated into VR interaction structures, particularly for K-12 learners whose cognitive characteristics differ from those of adult trainees.

Although several reviews have examined VR applications in safety training and medical education [3][8], systematic design methodologies for translating K–12 safety curricula into interactive VR systems remain limited.

2.2 Content Transformation Challenges in VR Educational Systems

Virtual reality (VR) technology, with its immersive and interactive characteristics, provides a promising approach for addressing these challenges [6].

Grounded in embodied cognition theory, VR allows learners to acquire knowledge through perceptual–motor interaction rather than purely symbolic processing [7]. However, despite the increasing accessibility of VR hardware, challenges remain in the development of educational VR content.

Many VR safety education systems still replicate traditional instructional materials within three-dimensional environments, such as static text panels or linear instructions. In other cases, developers focus on visual realism without integrating meaningful instructional interaction [9].

From a system design perspective, standardized frameworks for transforming textual curricula into dynamic VR interaction scripts remain limited. As a result, many VR educational systems function as "three-dimensional electronic textbooks", restricting their potential for procedural learning and embodied skill acquisition.

3 Design Methodology: From Text to Interaction

3.1 Stage 1: Behavior-Based Knowledge Decomposition

To transform safety instructions into VR interaction scripts, this study proposes a PDA interaction mapping model, which decomposes instructional content into three hierarchical interaction layers.

①Cognitive primitives: Recognizing environmental information such as alarms or exit signs.

②Decision primitives: Making evacuation decisions under emergency conditions.

③Action primitives: Performing physical safety behaviors such as crouching or covering the mouth.

This decomposition converts textual instructions into programmable interaction nodes that can be implemented in VR environments.

3.2 Stage 2: PDA Interaction Mapping Model

To operationalize the aforementioned interaction primitives within the Unity 3D engine, a PDA mapping model was developed [10]. As shown in Figure 1, this model moves beyond the didactic reliance on traditional UI panels and instead emphasizes environmental storytelling as the primary instructional mechanism. The PDA mapping framework consists of three layers—Perception, Judgment, and Action.

Through this classification, abstract textual chapters were transformed into a list of programmable interaction nodes, thereby establishing a logical foundation for subsequent scene development.

Based on the PDA framework described above, the FireEscape-VR prototype system was developed. A representative transformation case is presented as follows:

Textual instruction: "In the event of a fire, cover the mouth and nose with a wet towel."

VR implementation:

①P (Perception): A towel and water source are placed in the environment as visual cues.

②A (Action): The user grabs the towel and wets it under running water.

③D (Decision): If the user ignores this step and enters a smoke area directly, the system blocks task progression.

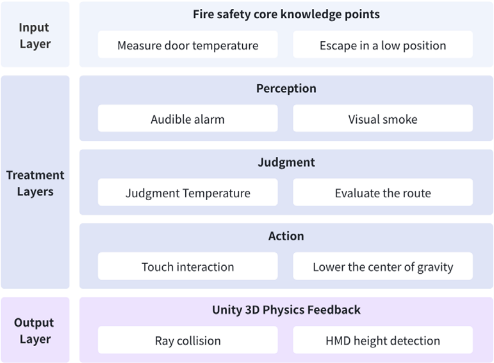

Fig. 1. Architecture diagram of the PDA interaction mapping model for the FireEscape-VR system

4 System Implementation and Case Demonstration

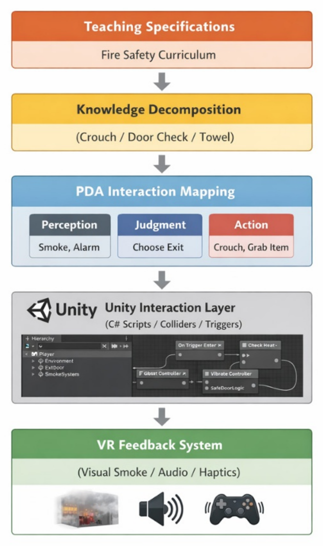

Fig. 2. System architecture of the PDA-based VR fire safety training system implemented in Unitysystem

Based on the PDA design framework described above, a prototype system named FireEscape-VR was developed using the Unity 3D engine. Figure 2 illustrates the system architecture used to implement the PDA interaction mapping model within the

Unity engine. This section outlines the system's development environment and presents two representative interaction cases—crouched evacuation and door temperature detection—to illustrate the concrete transformation of the proposed framework from conceptual design to engineering implementation.

4.1 Case 1: Posture-Based Smoke Feedback

In conventional safety education, the instruction to "evacuate in a crouched posture" is typically delivered as a verbal slogan. In the present system, this rule is implemented as a real-time interaction between body posture and environmental feedback.

Implementation logic: The vertical position of the head-mounted display (HMD), obtained from Transform.position.y, is used as the evaluation parameter. During initialization, the user's standing height is calibrated and a dynamic threshold (Height_Threshold) is set at approximately 60% of the user's height.

Interaction mechanism: The system continuously monitors the user's vertical position.

①State A (Safe Posture): When User_Y < Threshold, the system determines that the user is crouching. In this state, the visual field remains clear and movement is unaffected.

②State B (Hazardous Posture): When User_Y > Threshold, the system interprets the user as standing. Instead of displaying explicit UI prompts, the system increases smoke opacity and triggers coughing audio as corrective feedback.

Design Rationale: This strategy uses negative feedback to encourage posture adjustment. By requiring users to lower their body position to regain clear visibility, the system reinforces safety skills through procedural experience.

4.2 Case 2: Door Temperature Detection

"Checking the door handle temperature before opening a door" represents a critical decision point for assessing fire proximity. In this system, this tactile perception is simulated through controller-based haptic feedback.

Scene setup: Two visually identical doors are placed in a corridor. Door A leads to a safe passage, while Door B is located near the fire source.

Interaction logic:

①Collision detection: When the user's virtual hand touches the door panel or handle, an OnTriggerStay event is triggered.

②Variable mapping: The system reads the Fire Intensity parameter of the area behind the door.

③Haptic feedback: If the user touches Door B, the controller generates a vibration pulse (Amplitude: 0.8, Duration: 500 ms) to simulate a "hot handle", accompanied by subtle fire sounds.

Outcome presentation: If the user ignores the haptic warning and opens Door B, the system triggers a backdraft effect and displays failure feedback.

Design rationale: This interaction converts the invisible property of heat into a perceivable vibration cue, helping users avoid entering the hazardous room.

5 Expert Evaluation

To evaluate the instructional validity of the proposed framework, an expert review was conducted.

5.1 Participants

Three secondary school safety education teachers with more than ten years of teaching experience participated in the evaluation. Each expert experienced the full VR fire evacuation scenario using a head-mounted display and then participated in a semi-structured interview.

5.2 Evaluation Results

After transcription and thematic coding of the interview data, the expert panel expressed strong overall approval of the system's design framework.

(1)Content accuracy: From slogans to standardized procedures

Experts highlighted that the system effectively transforms abstract textual safety regulations into enforceable behavioral constraints. In traditional classroom instruction, teachers often find it difficult to ensure that students perform safety actions correctly. The VR system addresses this limitation by providing immediate behavioral feedback. In particular, the posture detection mechanism ensures that students must maintain a proper crouched posture to proceed, thereby improving the accuracy of safety behavior.

(2)Instructional logic: From passive transmission to active reasoning

Experts noted that the PDA interaction model aligns with constructivist learning principles. Instead of relying on explicit UI prompts, the system encourages students to interpret environmental cues such as smoke or heat to make decisions. This interaction design promotes active reasoning and increases cognitive engagement during the learning process.

(3)Overall evaluation

Experts further indicated that the system provides an appropriate level of immersion, enhancing students' awareness of fire hazards without causing excessive stress. Overall, the system was considered suitable as a virtual training component to complement existing safety education programs.

6 Conclusions

This study proposed a text-to-interaction transformation framework for VR-based fire safety education. The main contribution is the PDA interaction mapping model, which translates safety regulations into embodied VR interactions. Through the development of the FireEscape-VR prototype and two representative interaction cases, the feasibility of the framework was demonstrated. Expert evaluation indicates that the proposed design approach effectively supports the translation of instructional content into interactive training experiences. Future work will involve controlled experiments with student participants to quantitatively evaluate learning outcomes and skill transfer.

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