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APPLYING GAMIFICATION THEORY TO ENHANCE LEARNING EFFECTIVENESS IN VR CONSTRUCTION TRAINING

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Abstract

In the construction industry, occupational accidents account for 13.78% of all workplace incidents across various sectors, indicating a significant level of safety risk at construction sites. Therefore, reducing the incidence of accidents on construction sites has become a critical challenge in promoting occupational safety education. In particular, when it comes to educating workers on safety awareness and emergency response skills, traditional teaching methods typically relying on printed manuals fall short in realistically presenting high-risk site scenarios. Learners often lack hands-on experience, making it difficult for them to respond swiftly and appropriately during unforeseen incidents.

With advancements in technology, Virtual Reality (VR) has been widely adopted in various fields of education and training. By simulating real-life scenarios, VR enhances learners' sense of presence and practical experience. Furthermore, when combined with gamified learning strategies such as challenge-based tasks, reward systems, and role-playing interactions, VR can effectively stimulate learning motivation and improve training outcomes, enabling learners to absorb knowledge more proactively.

This study integrates VR technology and gamification design to develop a gamified virtual reality training system for construction safety education. By simulating realistic construction environments and common accident scenarios, the system provides a safe space for learners to engage in experiential training. Through the use of game mechanics, it further boosts learners' engagement and concentration, enabling the acquired safety knowledge to be applied in real-world operations, thereby reducing the risk of occupational accidents on actual construction sites.

Keywords: construction, gamification of learning, occupational safety education, virtual reality.

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1. Introduction

According to the 2023 Labor Inspection Statistics published by Taiwan's Occupational Safety and Health Administration (OSHA) of the Ministry of Labor [1], the construction industry accounts for 13.78% of all occupational accidents, ranking second among all industries. This highlights the significant safety risks present in construction environments and underscores the importance of safety training for on-site personnel.

However, current safety education is still predominantly delivered through traditional printed manuals or instructional videos, which fall short in realistically simulating hazardous situations. As a result, learners often lack the emergency response capabilities needed to react effectively in sudden, high-risk scenarios. With technological advancements, Virtual Reality (VR) has been increasingly applied in education and training, offering immersive and interactive learning experiences that enhance learner engagement [2]. At the same time, gamified learning strategies, which incorporate challenge-based tasks and feedback mechanisms, have been shown to boost learning motivation and outcomes[3][4].

Therefore, this study integrates VR technology and gamification into construction safety education and training. A training system that features realistic environmental simulations and interactive challenges has been developed to enhance the safety awareness and emergency response skills of construction personnel, ultimately aiming to reduce the risk of occupational accidents.

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2. Literature Review

2.1. Application of Virtual Reality Technology in Educational Training

Traditional occupational safety training often relies on lectures, printed materials, or video-based instruction. While these methods can effectively convey fundamental knowledge, they are limited in their ability to simulate complex scenarios and develop practical skills[5]. Recent studies have shown that compared to conventional teaching materials, VR-based education offers enhanced immersion, presence, and interactivity characteristics that help address the challenges of abstract knowledge comprehension and insufficient hands-on experience commonly found in traditional instructional contexts[6].

By simulating hazardous construction environments without posing actual risks, VR allows learners to engage in experiential training that fosters hazard recognition and emergency response skills. This capability significantly improves the overall effectiveness of safety education and training programs [7].

2.2. Fundamental Theories and Design Elements of Gamified Learning

Although VR has demonstrated significant advantages in education such as enhancing immersion, presence, and the ability to simulate high-risk environments, research [8] suggests that passive browsing or limited interaction in VR alone may not be sufficient to sustain learner motivation or improve performance over extended periods. To address this, gamified learning introduces game-based logic and mechanisms into educational activities, increasing interactivity and engagement. This approach encourages learners to engage in self-directed actions, strategic thinking, and knowledge construction[9][10]. Therefore, integrating gamification into VR learning environments can help overcome the limitations of passive VR instruction and fully unleash the potential of immersive learning.

Game elements, when applied in non-game educational contexts, serve as instructional strategies to increase motivation and participation. research [9] defined five core components of game design commonly used in gamified learning:

- Game Interface Design: Visual and interactive components such as rewards, badges, leaderboards, and levels often used in feedback systems to reinforce learner behavior.
- Game Mechanics: The rules and play dynamics, including time limits, resource management, and turn-based actions, that structure learning interactions.
- Game Principles: Evaluation guidelines used to design tasks with clear goals and diverse styles to enhance problem-solving and learner engagement.
- Game Modules: Conceptual models of game experience such as challenge mode, cooperation, or storytelling, which increase emotional involvement and immersion.
- Design Methods: Practical approaches to game development, such as iterative design processes that emphasize player-centered experiences.

Building on these five dimensions, Sailer et al.(2017) [10] proposed three commonly used gamification sub-elements, which operationalize core concepts and are frequently applied in educational systems:

- Points: Used as feedback and to track learning progress, such as experience points, reputation scores, or redeemable credits.
- Narrative/Storytelling: Contextual narratives that frame learning tasks, enhancing emotional engagement and content relevance.
- Teammates: Real users or Non-Player Character (NPC) that support collaborative or competitive dynamics in learning.

By combining these core and sub-elements, gamified learning enhances the fun and interactivity of instructional activities. It also fosters learner motivation to engage in tasks and supports active participation through challenges and contextual learning, ultimately strengthening knowledge construction and skill development.

3. Development of an Occupational Safety Education System Using Gamified Virtual Reality

This study developed a vocational safety learning system for the construction industry that integrates gamified learning strategies with VR technology. The system simulates high-risk operational scenarios commonly found on construction sites and enhances learners' hazard recognition and problem-solving

abilities through interactive tasks and real-time feedback mechanisms. This chapter presents the system design framework, including the contextual scenarios, virtual environment construction, gamification elements, instructional content, and the development of functional modules.

3.1. System Scenario Planning

According to statistical data on major occupational accident types published in the Labor Inspection Report, this study selected the most common and high-frequency hazard categories as the foundation for designing game-based training scenarios. The system primarily focuses on two major types of construction hazards: structural collapse and falls, including falling objects. To simulate realistic high-risk operations, the training scenario centers on scaffold erection, a representative task associated with these hazards. By recreating such environments in a virtual space, the system aims to enhance learners' sense of immersion and situational awareness in hazardous construction contexts.

3.2. Construction of a Virtual Construction Site

In this study, a realistic virtual construction site was created by integrating Revit and Unity3D to enhance the system's sense of immersion. This setup allows learners to interact and perform tasks within a virtual environment, as illustrated in Fig. 1. The design of this environment supports the development of spatial awareness, hazard recognition, and response capabilities in construction scenarios. By simulating real-world operations, the virtual environment reduces the learning barriers and safety risks associated with on-site training.

Fig. 1 Scaffold assembly operation scenario in the virtual construction environment.

3.3. Design of Gamified Interactive Mechanisms

To integrate occupational safety education into an immersive digital learning environment, this study adopts the core elements of gamified learning as the foundation for game design, aiming to create a learning experience that emphasizes exploration, interactivity, and contextual immersion. The system is primarily designed as an adventure-exploration game, incorporating learner-centered interactions. Through task-based progression and feedback mechanisms, learners are guided to actively engage in learning and risk identification, thereby enhancing their safety awareness and practical competence.

The gamified system design introduces core mechanisms across four dimensions: game modes and mechanisms, game design methods, user interface design, and reward and motivation mechanisms. Each dimension is explained as follows:

3.3.1. Design of Adventure-Exploration Game Flow

In the gamified learning system developed in this study, an adventure-exploration type game is adopted as the main mode to encourage learners to actively explore unknown environments and uncover potential safety hazards in construction settings, thereby enhancing their problem awareness and situational perception, as shown in Fig. 2.

By interacting with virtual objects, learners are not only required to identify problems independently but must also collect and manipulate virtual tools to complete designated tasks, as illustrated in Fig. 3.

The system emphasizes not only interactive challenges and problem-solving, but also features a mechanism that provides immediate feedback when learners resolve an issue, encouraging active

participation in the game. Through this, learners are motivated to learn from their mistakes and to understand construction safety regulations through hands-on interaction. Rather than passively receiving information, learners are driven to discover problems proactively and propose solutions, thereby cultivating their risk identification and prevention abilities.

Fig. 2 Identifying Missing Safety Components

Fig. 3 Resolving Potential Safety Hazards

3.3.2. Design of Contextual Narratives and Task-Oriented Structures

To enhance the narrative realism of the gameplay experience, the system incorporates a story-driven context and a mission-based exploratory process. Learners interact with NPCs to receive task-related guidance and relevant information, thereby increasing the interactivity and logical flow of the training process. This approach allows learners to experience a more coherent and goal-oriented learning journey throughout the operation.

To achieve this, the system introduces a storyline-based design, assigning learners the role of a safety inspector who must actively patrol the virtual site and complete safety inspection missions. During these missions, learners can interact with NPCs such as asking on-site workers about potential hazards, obtaining tools, or receiving hint-based prompts which help guide them through each challenge and assist in completing the tasks, as illustrated in Figure 4.

Fig. 4 NPC interaction providing task guidance.

3.3.3. Design of Interactive User Interfaces

To improve the VR interaction experience and streamline the learning process, the system features an intuitive user interface, including elements such as dialogue boxes and a game backpack interface, as shown in Fig. 5. The backpack interface provides real-time updates, allowing learners to view and manage the collected game items. This design enhances operational efficiency, clarifies task progress, and ensures a smoother and more engaging interaction throughout the training experience.

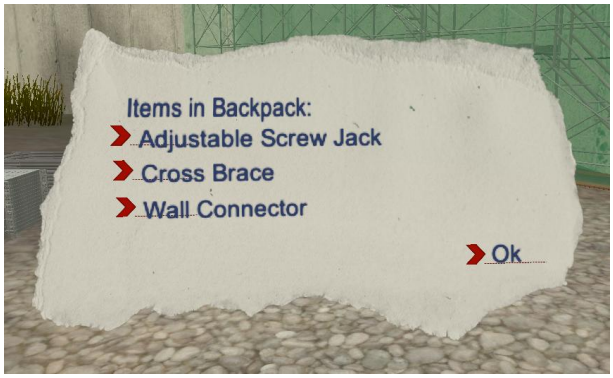

Fig. 5 Game backpack interface.

3.3.4. Task Rewards and Learning Motivation Strategies

To enhance learners' motivation for challenges and promote sustained engagement, the system incorporates a reward mechanism that includes virtual incentives such as game coins and functional items. When a learner successfully completes a designated task, the system provides virtual rewards. For example, after repairing a safety hazard, the learner receives a mission-related item in Fig. 6, which can be used in subsequent levels. These rewards are designed to increase learners' sense of achievement and encourage continued participation in future challenges, thereby improving overall learning motivation and engagement.

Fig. 6 Game rewards: receiving in-game items after completing tasks.

The design of these gamification elements is based on the core and sub-elements of game design discussed in Section 2.2, and is tailored to the context of virtual reality-based instruction. This study integrates an adventure-exploration game model, story-driven and mission-oriented guidance, intuitive user interfaces, and reward-based feedback mechanisms to construct an immersive and challenge-rich gamified learning environment.

Through active participation in simulated real-world scenarios, learners are guided to identify hazards, propose solutions, and develop practical problem-solving skills. The system enhances both risk perception and hands-on capabilities, while also increasing learner engagement and enjoyment in safety training activities.

3.4. Instructional Knowledge Design

To ensure the accuracy and practicality of the occupational safety knowledge delivered through the gamified learning system, the instructional content in this study was compiled and designed based on current occupational safety and health regulations in Taiwan. The legal and regulatory references

include the Standards for Construction Safety and Health Facilities, the Regulations for Occupational Safety and Health Facilities, and the Scaffold Operation Safety Inspection Guidelines and Key Points issued by the Occupational Safety and Health Administration, Ministry of Labor.

3.5. Development of Interactive System Functions

To enhance the interactivity and fluency of the gamified VR learning system, this study utilized the Unity3D game engine as the development platform. By leveraging built-in modules and custom C# scripting, two core gamified functions were developed: Object Placement Control and Game Backpack Management. These functions serve as the central mechanisms during gameplay, allowing learners to interact in real time with the virtual construction environment and complete tasks, thereby strengthening the immersive learning experience.

3.5.1. Virtual Object Placement Control Module

To assist learners in interactively correcting safety deficiencies within the virtual construction site, the system incorporates a drag-and-align mechanic that allows objects to be accurately placed in designated positions. The system automatically adjusts the object's angle and scale and plays a confirmation sound upon successful placement to provide immediate feedback. This feature encourages active participation in scaffold configuration tasks and enhances learners' ability to recognize improper installations, fostering greater sensitivity to safety risks in construction settings.

3.5.2. Task Item Management Interface Module

To improve learners' operational efficiency and task management within the virtual environment, the system includes a Game Backpack interface as the core hub for item tracking and mission control. Using VR controllers, learners can intuitively access the backpack to view collected items and monitor task progress in real time in Fig. 7. The contents of the backpack dynamically update based on user interactions. Once all target items are correctly placed, the system automatically displays a "Mission Completed" prompt to guide learners to the next level.

This function not only enhances usability and supports smooth task progression, but also helps learners integrate mission-related information and develop practical competencies such as logical reasoning, resource management, and problem-solving skills.

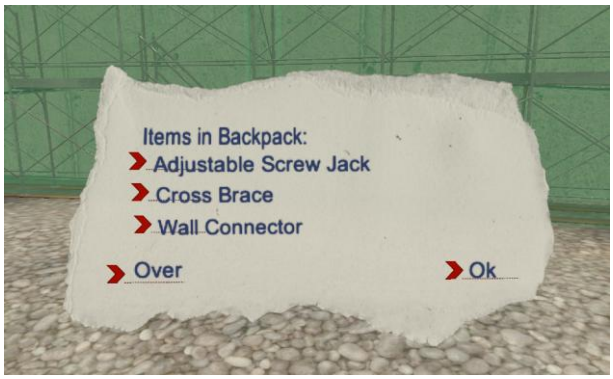

Fig. 7 Game Backpack interface displaying collected items and mission progress.

In summary, this chapter presented the development of a digital learning system based on the theoretical foundations of virtual reality and gamified learning, integrating core concepts from occupational safety education. Centered around a scaffold assembly scenario, the system incorporates a variety of gamification elements including adventure-based exploration tasks, interactive NPC guidance, real-time feedback, mission challenges, and reward mechanisms to create an immersive and goal-oriented learning experience.

Additionally, the user interface and interactive features were developed using Unity3D and custom C# scripting, with key components such as object placement control and the game backpack module designed to improve the ease of interaction and overall control of the learning process.

The overall system design not only increases learners' motivation and engagement with occupational safety content, but also enhances their ability to identify risks and solve problems within a simulated construction environment.

4. Conclusion

This study proposed a construction safety education system that integrates virtual reality technology with gamified learning strategies. By simulating realistic construction site environments and incorporating gamification elements such as task-based learning, real-time feedback, role-playing, and reward mechanisms, the system creates an immersive and engaging digital learning experience. The overall design is based on an adventure-exploration game model, in which learners take on the role of safety inspectors, freely explore the virtual site, interact with NPCs, identify potential hazards, and complete corrective tasks.

To promote active learning and knowledge acquisition, the system features an intuitive user interface and interactive control mechanisms that guide learners to gradually master hazard identification and emergency response strategies through hands-on operation. This helps improve both their conceptual understanding and practical application of construction safety knowledge.

This research currently focuses on the development of the system architecture and core functional modules. Future studies will adopt experimental designs and pre/post assessments to evaluate the system's impact on learning outcomes and safety awareness. These results are expected to provide empirical support and practical reference for the application of virtual environments in occupational safety education.

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