Conceptual Framework for Evaluating Construction Safety Awareness Using Virtual Safety Games

Sabnam Thapa[1] and Vachara Peansupap[2]

[1,2] Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand
**Corresponding author; E-mail address: vachara.p@chula.ac.th.*

Abstract

The construction industry is considered one of the most dangerous jobs globally, and lack of safety awareness is a major cause of accidents. Therefore, it is essential to evaluate the level of safety awareness among construction personnel at the site. Past research attempts evaluated safety awareness levels based on passive methods such as questionnaires and interviews, but these are self-evaluated and do not assess the ability of the person to apply safety knowledge in real-world scenarios. Recently, Virtual Reality (VR) games have been widely recognized for their applications in safety education and training and have been effectively used to assess safety knowledge, attitude, and hazard inspection. This research aims to develop a framework for assessing the existing level of safety awareness using VR games. The Input-Process-Output (IPO) model has been a popular game design model with improvements in components of game characteristics in the newer IPO models. Based on the ideology of these methods, a new conceptual framework was developed to assess safety awareness, which consists of safety knowledge and hazard detection as indicators. The details of steps involved in developing the key components of game design are explained in detail. In this research, safety awareness has been recognized in terms of safety knowledge and hazard detection. Player performance is reflected in each indicator; therefore, it provides clarity on the areas of awareness in which players lack or excel and can be managed accordingly. Thus, this framework can be used as a guideline in the development of assessment tools for safety awareness with VR games.

Keywords: Construction safety, Safety awareness, Virtual reality game, Safety knowledge.

1. Introduction

According to the BLS report for 2021, the construction and extraction industries had the second-highest number of occupational deaths in 2021 despite a 2.6% decrease in fatalities from 2020. Thus, despite the drop in fatalities, the construction industry continues to be one of the most dangerous occupations. Lack of construction safety awareness accounts for one of the major causes of accidents [1, 2].

Therefore, there is a need to measure the existing level of personnel safety awareness at the construction site to prevent accidents. Even though the traditional method of assessing safety awareness levels using questionnaires and interviews has been the standardized practice of measuring safety awareness levels [3, 4], they are limited in evaluating practical skills in real-life conditions, which is necessary for assessing safety knowledge and hazard identification, inherent to safety awareness.

2. Problem statement

Recent studies demonstrated VR games' potential in providing a realistic and immersive experience, being customizable to safety needs, engaging users, and providing an instant assessment of performance [5]. VR games' characteristics have been found helpful in safety training, education, and assessment [6-8]. Particularly, VR games have demonstrated their ability as effective hazard awareness and safety knowledge assessment tools. However, limited research has applied VR games as an assessment tool to evaluate safety awareness using safety knowledge and hazard detection skills. Thus, this research aims to develop a conceptual framework for assessing safety awareness levels using VR games. The potential and drawbacks of this method for assessing safety awareness levels are evaluated.

3. Literature review

The literature review provides background knowledge and theory which are factors affecting construction safety awareness, methods for assessing safety awareness, VR games as assessment tools, and the concept of game design and development. The details of each topic will be described below.

3.1 Factors affecting construction safety awareness

Previous studies have identified several factors that influence safety awareness, including training. Improving safety awareness is a crucial aspect of any organization, and safety training has been identified as the most effective method to achieve this. It is widely acknowledged that safety training directly influences awareness levels and helps ensure a safe and healthy work environment [9]. A virtual environment simulation of electrical hazards was done to train workers on electrical safety. It was found to improve users' awareness and cognitive abilities in electrical hazards at the workplace [10]. The study conducted aimed to identify the most effective safety training method between conventional lecture and 3D BIM-based simulation. The results showed that the 3D BIM-based simulation method improved the understanding of the contents of the training, highlighting its potential in enhancing safety awareness. The study concluded that BIM was the superior method and emphasized the crucial role of effective training in promoting safety awareness.[11]. Similarly, a study that was intended to determine the impact of safety training evaluation on safety performance found that safety training besides reducing accident rates also resulted in improved safety awareness and overall safety culture improvement [12]. Along with safety training, safety education has also been found to influence safety awareness. For example, a study on aviation safety education showed that clear instructions in safety education can have a positive impact on safety awareness, including a cabin's safety knowledge, attitude, and behavior [13]. In another study, the use of a developed VR-AR-based mobile framework to teach safety knowledge and hazard detection resulted in increased awareness among students [14]. Furthermore, safety leadership and culture have been shown to improve safety cognition and awareness, leading to lasting behavioral change [15].

Several other research studies have explored various ways to improve safety awareness, such as using smartphone applications for collision detection, formal daily huddle meetings, safety communication, and recognition programs [15]. In addition to these methods, the lack of safety knowledge is a major contributing factor to lower safety awareness [3]. While studies have used the terms "knowledge" and "awareness" interchangeably, they are not the same. Factors such as attitude, behavior, motivation, and commitment have also been used to refer to safety awareness [12, 16]. Moreover, hazard identification abilities are integral to awareness [17]. Therefore, this study measures safety knowledge and hazard recognition as indicators of awareness, as is done in OSHA's training requirements and student manuals.".

3.2 Traditional Methods of assessing safety awareness

Surveys and interviews are commonly used as assessment tools for measuring safety awareness. In a study conducted in Botswana, a survey questionnaire was used to determine the low level of safety awareness among workers [3]. Another study conducted in Konya determined metal workers' low levels of awareness of safety issues [16]. Similarly, a survey was used to assess the awareness level of workers regarding the use of PPE equipment, which was found to be moderate [16]. However, another study found that despite being aware, employees' awareness was not reflected in their practical behavior [4]. Interviews and surveys are time-consuming and prone to recall biases [18], making them more suitable for understanding people's opinions, perceptions, beliefs, experiences, and knowledge [19]. On the other hand, VR games have shown potential in simulating hazardous scenarios in a risk-free environment, increasing engagement and motivation, providing immediate feedback, and tracking players' progress [20, 21]. Therefore, there is a need to explore the use of VR games in assessing safety awareness.

3.3 VR Games as an assessment tool

Some studies have used VR as an assessment tool. By developing a virtual safety training system in the Virtual safety assessment system (VSAS), the study evaluated the safety knowledge and attitude of workers by developing visualizing of unsafe sites, unsafe behavior, and unsafe working methods and quizzing with the question database. However, it provided a non-immersive VR experience, presented only a third-person perspective and navigation and user control were difficult [17].

A location-based game was developed to assess the safety knowledge and risk perception of workers, but it had only static questions meaning the game couldn't be played again and again and provided with a non-immersive virtual experience [8]. By developing an Augmented virtuality game to train workers, the game offered direct feedback on workers' behavior after the training. However, the game only had performance evaluation at the end of the game, and there were doubts about players choosing appropriate elements based on knowledge or random chance. [15]. In another study, System for Augmented Virtuality Environment Safety (SAVES) integrated the Building Information Model (BIM) with photographs of typical energy sources to elevate safety awareness, enable hazard prediction and identification, and assess severity while evaluating trainees on choices made, decision-making time, and prevention plan. Although SAVES is a system that combines hazard data, best practices, and safety regulations to create well-designed training scenarios in a BIM model, its engagement of workers is lesser given that it is VR based on assessment [18]. Therefore, there is a need to develop an assessment tool to measure safety awareness with a fully immersive VR game with a first-person perspective, an easy-to-navigate system, random questions, and an engaging virtual environment while overcoming the above-mentioned gaps. Thus, this research focuses on developing a conceptual framework for the design of VR games to act as an assessment tool for measuring safety awareness.

3.4 Concept of game design and Development.

To develop an effective game-based assessment tool, it is imperative to understand the core characteristics of instructional games and the fundamentals that contribute to creating an interesting game. Therefore, two of the most relevant research papers were referred to as follows.

3.4.1 The Input-process-output (IPO) model for game design.

The IPO model is a game design model developed to aid in the design of instructional games [18]. The primary objective of the model is to create engaging games that promote self-learning through repetition. To achieve this, the study focused on the three main components of the IPO model: game characteristics, game cycle, and learning output [18]. The game characteristics highlight core elements of instructional games, including fantasy (the environment of the game), goals and rules of the game, and sensory stimuli such as perception and sound effects. Other characteristics include challenges (to keep players engaged), mystery (to increase curiosity), and control of movements. The game cycle is a feature of gameplay that makes games engaging through a repetitive cycle of the judgment-behavior-feedback loop [19]. The game cycle functions to make players repeatedly play the game (behavior), ensure that players enjoy the game (judgment), and user interaction and scores (feedback). The learning output of the IPO model focuses on the desired skills or knowledge the players need to have after playing the game.

There are several pros and cons of the IPO game model. IPO-based game designs are customizable to suit different needs and can be used repeatedly. This type of game-based learning incorporates dynamic learning which includes repeated testing instead of learning contents and giving exams only once [19]. Furthermore, giving student control over the game and keeping scores as performance feedback makes this instructional method interesting and engaging [19]. However, creating such games requires high expertise and significant time investment. Additionally, game-based learning may be distracting to some learners or may even become addictive[19, 20]

Due to the various advantages offered by the IPO game model, some games have incorporated this concept into their designs. For the development of hazard detection training in construction, the design phase utilized three components of the IPO model: instructional design, game characteristics, and user characteristics [20]. Another study improvised the IPO game model to create a conceptual framework for designing serious games [21]. Since the IPO game design model has been widely accepted and utilized in the design of instructional games, this research will use the IPO model for developing the conceptual framework. Some of the core elements of the IPO model that the research will apply to include game characteristics and the concept of the game cycle.

3.4.2 A conceptual framework for serious games.

Using the concept of the IPO game design model, a new conceptual framework was developed for the serious game that provided more structure to game design [21]. As a derivative of the IPO model, the conceptual framework brought clarity into the steps involved in the game design such as breaking down the game characteristics of the IPO model into game mechanics,

and genre. This research revised the traditional IPO processes component by introducing a new element called capability which ensures that the objectives for game design are set up at the beginning instead of setting outcomes in the end, like the IPO mode [21]. Furthermore, the research to ensure cognitive, skills or affective skills after the game in the beginning as capability, at the end as game achievement, and as reflection. While the standard IPO model directly starts with instructional content and game characteristics, the new model begins with the outcome by incorporating "capability", setting an aim for the model development at the start which helps in directing consecutive actions. Representing the "game cycle" component, this improved model includes a collection of feedback, reflection, achievement, game mechanics, and game genre, in one big loop. Furthermore, the game mechanics component is an extension of rules/goals like the IPO model. Although both models provide an overall guideline for conceptual framework development, clarity on the development of the game cycle is still required. The two studies also focused on the use of facts, concepts, procedures, and principles to ensure learning, but they did not include questions/quizzes in instructional content.

4. A conceptual framework for the assessment of safety awareness

The development of assessment tools includes developing questions to be asked in addition to the other processes and characteristics involved in creating an effective instructional game. This conceptual framework is an evolution of the IPO game design model and a new conceptual framework for serious game design [19, 21]. To provide structured guidelines for the development of VR games for the assessment of awareness, the following subparts provide details. Fig.1 shows the conceptual framework.

4.1 Input

As the first component of the conceptual framework, this component of the conceptual framework is developed to collect information based on which the game is designed. It consists of two parts, which are capability and game design. Firstly, capability consists of information about the users for whom the game was designed. Second, the game design focuses on the features to be developed in the game.

4.1.1 Capability

Derived from the modified IPO model, this characteristic of game design determines the skills and knowledge the game should assess and improve in its players. Based on the targeted audience, this section will differ. For example, if the game is designed for students who have no experience in construction, the game and its contents will be designed to familiarize them with the basics of safety knowledge and hazard recognition skills. To develop an effective assessment tool, it is important to develop the right questions to assess the players.

The questions development is one of the most important steps in the conceptual framework for the assessment tool since dictates the choice of the game environment, how the questions are triggered, and the method of evaluating the player's performance. Using the concept of instructional content the following question prompts were devised to assist the designer to develop relevant questions [19, 21]:

- How will the question assess the player's safety knowledge on the subject?
- How will the question assess the player's hazard detection skill?
- Which issue of safety does the game focus on?
- What kind of scenario will best simulate the hazardous conditions?
- How will the question's complexity change as the game progresses?

4.1.2 Game design

The game design component involves the development of features and properties that will be incorporated into the VR game. It is divided into smaller parts to specify precise functions required from its elements. Based on the developer's technical capability, time availability, and the objective of the game, game features are chosen and designed. Although there are many more attributes to game design as explained as "game characteristics" and game attributes" in the game models, the research chose the most fundamental attributes necessary for game design.

The game's theme serves as the underlying storyline that connects players to the game, shapes the game design, and distinguishes it from other games. In the case of a VR game, the theme plays an especially crucial role in creating an immersive

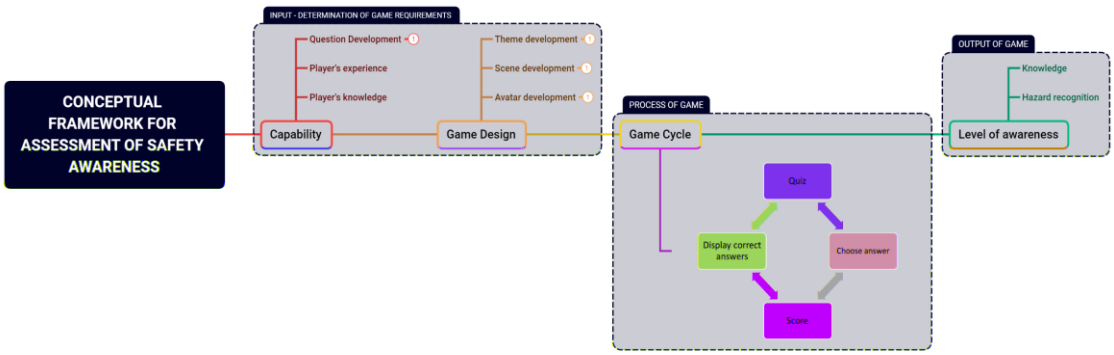


Fig. 1 The Conceptual Framework for Assessment of Safety Awareness.

and captivating experience for the player. It influences the game's genre, scenario, character, and interaction development.

Table 1 Themes for development of a conceptual framework in the assessment of safety awareness.

Scene	Assessment of Safety Knowledge			Assessment of hazard identification	
	Level 1- Finding the correct PPE	Level 2 – Find components or functions	Level 3 Function or specifications of components	Level 1 Identify hazards	Level 2- Identify hazards
Scene 1	Scaffolding hazard	Scaffolding hazard	Scaffolding hazard	Scaffolding hazard	Falling hazards
Scene 2	Ladder hazard	Ladder hazard	Ladder hazard	Ladder hazard	Flying hazards
Scene 3	Flying hazard	Guardrails	Guardrails	Open space	Electrocution hazards

This research aims to measure safety awareness using safety knowledge and hazard identification skills as indicators. The game's theme is designed to evaluate safety knowledge by assessing personal protective equipment (PPE), components, and their inspection at three different levels. The player's ability to identify hazards for access equipment is evaluated to assess their hazard identification skills.

Based on the theme of the game, scenarios are developed for the game. A scenario is a playground where the game takes place, and the player interacts with its environment. By adding objects, and utilizing lighting, audio, and animations, scenarios are made as real as possible. This is especially important so that the player develops a sense of presence, feels immersed, and is motivated to play for a longer duration. For the mentioned theme, the Unity game engine was used along with visual studio and VRIF assets to code and interact with the scenario. Objects such as buildings and other 3D objects were taken from Sketchup, Turbosquid, etc. Some of the models were modified to suit the environment in Blender.

In this research, the scenarios, as per its theme, were developed into two modules. Module 1 is designed to test knowledge of hazards whereas Module 2 is designed to assess players' hazard identification skills. The two modules are developed to independently demonstrate the awareness level of the player. This is done so that the exact category in which the player excels or needs improvement can accurately be determined to be addressed accordingly. Players can choose to

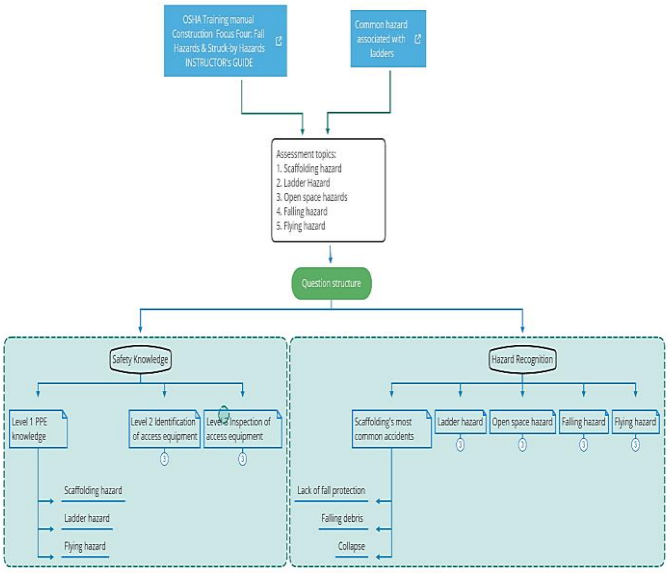


Fig. 2 The Assessment model's structure.

be assessed in any module. As shown in Figure 2, each of these modules has specific scenarios pertaining to specific hazards. For knowledge evaluation in level 1, the player is evaluated based on their knowledge of ladder, scaffolding, and open space safety. The theme for scaffolding hazards is the prevention of falls when working at height. To prevent scaffolding fall accidents when working at height, players are required to identify the correct Personal Protective Equipment (PPE). Based on this theme, the scenario is decorated with buildings and an animated non-player character (NPC) working at height without proper PPE. Other 3D objects that were relevant to the themes are also put on display to simulate real-life site conditions. A player's knowledge is evaluated based on the scores obtained from his/her ability to correctly identify the required PPE within the permitted time. To select the PPE, players must go near the 3D object and point/grab at it to score. Consecutive levels are more challenging, such as level 2 is to identify access equipment's parts and functions correctly. This is made to increase the player's motivation to play the game.



Fig. 3 System level 1: Select the correct PPE for the given task.

As for level 2, the scenarios were referenced from the most common accidents introduced in the OSHA's training manuals titled "Construction focus four: fall hazard and struck-by hazards" as well as from the official OSHA website. In this level, as shown in Figure 4, the players need to walk around the site to find hazards and click on the object to get the score. Each scenario is specific to its theme, such as for the open space hazard theme, players need to move around an under-construction high-rise building to identify hazards. Along with the main building scene, animated NPCs, and 3D objects such as cranes and other buildings are also rendered to make the scene look realistic environments.

The objective of developing an avatar and its control mechanism is to give a form to the main player. By being able to visualize oneself in a physical form, the player can relate to

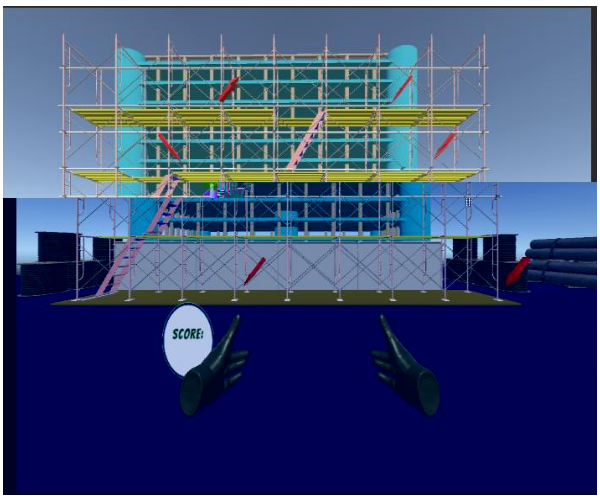


Fig. 4 System level 2: Identify hazard components and their functions.

the game better and even more so in a VR game when sensory stimuli are felt by the player. By means of game controls, the player interacts with their environment giving them a heightened sense of presence thereby increasing their immersion and motivation. The player in this game can move around using locomotion by pressing the controllers, with teleportation, and through WASD keyboard keys. In the game, the player must interact with UI elements to answer questions which can be done by the right-hand controller's pointer. To select objects, the player must use the right-hand controller pointer whereas to grab an object, the player uses the grip button. In this research, the VIVE HTC HMD and controllers have been the medium to interact with the virtual environment. The player form was directly used from the VRIF unity asset's XR advanced rig. Using the VRIF asset's XR rig, the player can see themselves as hands, and due to its high-performance built-in functionalities, the player can perform numerous actions like walking, teleporting, grabbing objects, throwing, pulling, pushing, and climbing to name a few. In the proposed game, the player's most common functions involve teleporting, walking around, grabbing objects, and interacting with UI.

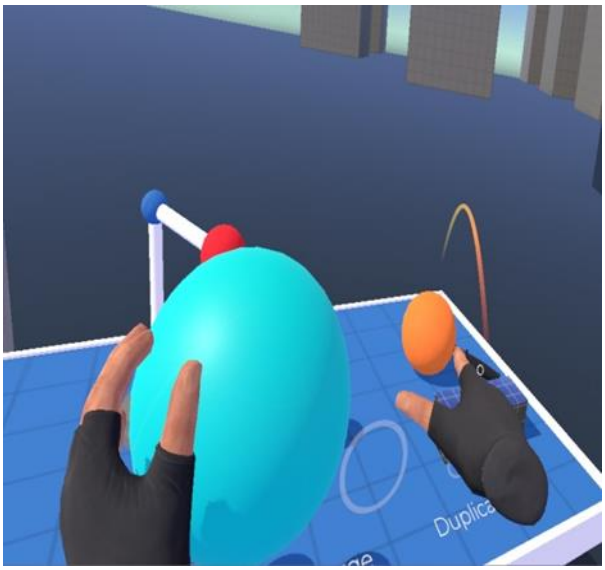


Fig. 5 Grabbing action with the grip button in the controller.

4.2 Process

The process is part of the game where the player initiates the game by interacting with its environment, other NPC, and interactable elements. As identified in the "game cycle" element and as a "learning activity" in the other study, the main objective is to keep the player engaged using challenging activities building engrossment and anticipation [19, 21]. It should consist of an optimal combination of challenges and rewards such that the game isn't too easy or difficult to disengage the player as well as to make the player repeat the process while also learning as posited by [19].

In this research, the modules for knowledge and hazard identification differ in their UI elements and question prompts. In the first level of the knowledge module, the game cycle is initiated when the player grabs the appropriate PPE. This action can add or subtract points from the player's score, incentivizing them to make correct choices. The timer begins once the player approaches the table (as depicted in Figure 3, which encourages them to select the correct objects quickly, creating a more engaging experience. If a player selects an incorrect answer, their score will be reduced, but the correct answer is also displayed to promote reflection and learning. The game cycle in the second and third levels of the knowledge module is initiated when the player approaches the arrow pointer. Each pointer and blinking components prompt a specific UI quiz that asks about the component and its function in level two and the specification and inspection in level three. The player must answer the question within the given timeframe. Feedback for every wrong answer is provided to help the player learn from their mistakes. To progress to the next level, the player must answer all the questions on the floor. This concept motivates the player to complete all the questions.

For the hazard recognition module, the game cycle is initiated when the player identifies hazards and clicks on them. When the correct object is clicked, a UI quiz is prompted with questions that ask the player to recognize the hazard and explain why it is a hazard. The scores for wrong answers are also displayed. By interacting with the objects and UI in this manner, the game cycle is designed to make the player more motivated to play the game repeatedly. As mentioned in the above sub-part, safety knowledge about fall hazards is defined in terms of players' accurate assessment of the safety equipment such as ladder and scaffolding based on knowledge about the main components of this equipment, OSHA's standard specifications for the components, their functions, and inspection standards. Thus, the player must move toward the pointers to trigger the quiz panel and answer within the time frame. Besides this, the questions are randomly generated so the player is compelled to play the game again and again to gain safety knowledge. Feedback is in the form of incremented scores as well as the ability to teleport to higher or lower elevations. For the hazard identification level, the player must move around the environment to identify unsafe conditions and unsafe acts and click on them. Only hazardous objects are interactable and for this, the challenge is to identify the correct object. Furthermore, to ascertain that the player is fully aware of the cause and type of hazard, quizzes are prompted to make the player identify the correct answers. The player at this level is motivated by finding the correct objects, answering correctly, and getting scores. The balance of questions, hazard identification, time limitation, and scores with instant feedback makes this phase engaging and stimulus repetition thereby increasing awareness.

4.3 Output

This represents the final phase of game development, aimed at improving skills or knowledge acquisition. The research framework developed here measures the player's current level of safety awareness while identifying areas of strength and weakness in either safety knowledge or hazard identification. By playing the game, players can receive instant feedback and

improve their safety knowledge, as well as sharpen their hazard detection skills. Moreover, the game's repeatability and randomization of questions make it a valuable tool for repeated use.

5. Discussion

The conceptual model developed for evaluating safety awareness was derived from the IPO model and the conceptual framework for serious games [19, 21]. The core components for game design, as postulated by the IPO game model, are Input-process-output[19]. In this research, the three core components are structured as per the IPO model into a conceptual framework for awareness assessment as shown in Figure 1. The main objective of the Input component is to gain insight into the target audience and to develop the virtual environment (VE) for gameplay. The capability subpart involves developing questions by understanding the end-user, as used by the serious game framework [21]. Using the capability elements that help understand target users and desired outcomes, the game design element is developed to create a virtual environment and player controls. After completing the elements of the input component, capability, and game design, the process components using their VE, avatar, and its controls, are in a loop of quizzing, getting answers from the player, awarding, or deducting points, and showing the correct answer if the player's response is incorrect. This loop continues until all tasks for each scene are complete. As noted in the study, the aim is to make the player play repeatedly to enhance learning [19]. The last component is the output expected from playing the game. It is expected that players will assess their level of awareness based on their total score in each scene. The objective is also to ensure that the players learn while playing.

The framework developed in this research follows the structure of the IPO model while incorporating elements of the framework for serious games. Both studies require clarity on the development of the game cycle with step-by-step guidelines, which were included in this research. Since the focus of both studies in the instructional content element included only facts, concepts, procedures, and principles, this research included developing questions/quizzes as instructional content, while also devising exemplary questions to generate more such content. Additionally, by relating the player's knowledge and experience to devise questions, competitive instructional content could be developed.

This research is a part of the design, development, and implementation of the VR game-based assessment tool to evaluate safety awareness. Following the development of the conceptual framework, a prototype will be constructed and played by students and safety engineers to ascertain its effectiveness. Based on user feedback and comparing the player's score, definitive conclusions about the tool's performance can be derived and validated.

6. Conclusion

This research focused on developing a conceptual framework for assessing safety awareness levels using VR games. Safety knowledge and hazard identification skills are used as the two indicators of awareness in this research. Improvising the popular IPO game model and its evolution, this conceptual framework was developed to assist in developing VR games to assess safety awareness levels. The conceptual framework emphasizes the essential components and their functionalities, providing a foundation for future work on awareness assessment. Future research could work on improving this conceptual model by introducing how the scenes could be generated in real-time when the capability is changed or based on the change in theme how scenarios could be automatically generated with relevant questions. Setting up a real-time question database could also improve the game.

The limitation of the current paper is the need to develop scenarios and questions to simulate different site conditions.

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