Asymmetrical Multiplayer Serious Game and Vibrotactile Haptic Feedback for Safety in Virtual Reality to Demonstrate Construction Worker Exposure to Overhead Crane Loads

Ingvild Moelmen, Haavard L. Grim, Emil L. Jacobsen, and Jochen Teizer

Department of Civil and Architectural Engineering, Aarhus University, Denmark
E-mail: elj@cae.au.dk, teizer@cae.au.dk

Abstract –

Construction still has high numbers of nonfatal and fatal occupational injuries. Works in highly dynamic and continuously changing environments involving heavy equipment pose numerous types of hazards. Potential struck-by incidents for pedestrian workers from overhead crane loads are a concern to many practitioners. Safety best practices suggest to avoid unsafe acts by early implementation of appropriate safety training. Serious games in Virtual Reality (VR) have proven efficient for such purpose because they engage and motivate the participants in the learning effort more than traditional methods can. However, most VR experiences are limited to one participant, and strict roleplay allows little interaction with the hazards. This paper demonstrates that an asymmetrical multiplayer serious game in VR can represent a more realistic work environment. The developed scenario contains several of the inherently embedded hazards and unpredictable human interactions involved in the specific use case of crane lift operations. Three players, of which two represent construction site personnel using head-mounted displays (HMD) and one operating a (gantry) crane using a remote desktop computer user interface, complete their work tasks in virtuality. Test results from 18 volunteering users, half of whom receive vibrotactile haptic feedback when confronted with hazards, show that such feedback positively impacts their hazard recognition rate. User awareness was also up to 35% higher while decreasing their time spent underneath a crane load.

Keywords –

Asymmetrical virtual reality, construction safety training, crane load hazards, multiplayer serious game, unsafe acts, vibrotactile haptic feedback

1 Introduction

The construction industry is one of the industries with the highest number of nonfatal and fatal occupational injuries. Construction operations can often be very complex and usually involve heavy equipment, various hand-powered machines and tools. As such, work in construction can be dangerous [1].

One of the leading causes of construction workplace accidents, according to the Occupational Safety and Health Administration's [2] 'Fatal Four', are struck-by accidents. The most common accidents involving lifting operations are related to struck-by incidents when workers are frequently within the danger zones of the crane or parts of it. In the latter case, these are, for example, loads that are attached to a crane hook [3].

For such reasons, construction workers receive appropriate safety training. However, traditional safety training methods in construction have been criticized for becoming less effective when participants demonstrate a low level of personal engagement [4]. Among many other reasons, Virtual Reality (VR) has been proposed as an additional method for the safety training curriculum. As earlier research has shown, VR has proven to be a useful method to enhance the visual understanding of complex work tasks in various industries [5].

Since construction workers are susceptible to accidents, VR tools have already been specifically researched to improve safety training [6]. VR can provide trainees with the hands-on experience of dangers as it simulates reality in a safe virtual work environment. This approach eliminates exposing any participant to real dangers and gives a more significant learning outcome than traditional methods, says Sepasgozar [7]. Nevertheless, VR still faces many socio-technical challenges that research needs to address.

For example, displaying struck-by hazards such as those coming from heavy equipment in VR serious games have typically been automated, following predefined paths in experiencing them [8,9]. To resolve this limitation for good, asymmetrical multiplayer VR serious gaming is proposed. It permits user interaction by applying different display devices (immersive head-mounted displays and desktop computer displays) [10].

The objective and scope of this study are to investigate construction worker safety, particularly their awareness of hazards in a dense and highly dynamic work environment. For this purpose, an asymmetrical multiplayer VR serious game is developed for testing participants in their roles of co-workers on an indoor construction site. Furthermore, the impact of receiving vibrotactile haptic feedback is studied. While individuals of one group of the participants receive the feedback in the form of warning signals as soon as they encounter danger, the ones belonging to the second group do not.

The following sections first review the most relevant construction safety background. The method section introduces a first-of-a-kind asymmetrical multiplayer VR serious game for construction safety training. While this work is still a prototype, early testing with participants is explained. Results that are encouraging lead to the section of implementation, limitations, and future work.

2 Background

2.1 Crane safety numbers and safe operation

Struck-by incidents are among the leading causes of fatalities in the construction industry. In 2019 struck-by hazards accounted for 15% of all construction fatalities in the United States [11]. It is also the largest contributor to nonfatal injuries in the construction industry, with 23.4% in 2019 [11]. Struck-by accidents account for many different hazards, including struck by heavy equipment and other vehicles, such as excavators, dump trucks, cranes (tower, mobile, gantry), or parts of thereof.

The most common accidents related to struck-by incidents involve lifting operations where workers are within the *danger zone* of the crane (def. *area where harmful contact(s) can occur with either the equipment itself or part(s) of it*) [1]. Hoisting operations are essential during construction projects. Cranes often operate with loads both near and above workers, often in crowded work areas that at times overlap with multiple crews on the ground [12].

The US Bureau of Labor Statistics reported 297 crane-related fatalities between 2011-2017 [13], of which over half involved a pedestrian worker being struck by moving parts or falling objects.

Recent years in the construction industry have seen a steady increase in the lifting operations performed on construction sites and off-site. One reason is the industry's trend towards using more prefabricated elements and modular building components [14]. Given the weights and sizes, such elements require lifting at some point in time in the construction supply chain and assembly process.

Therefore, Fard et al. [15] investigated 125 accidents related to modular and prefabricated building components. The results showed that 62% of those accidents occurred on the construction site, and most were experienced during the installation task.

A similar analysis on accidents related to prefabricated elements was carried out by the Norwegian Labor Inspection Authority [3]. It investigated 21 accidents. In over 50% of the identified accident cases, workers were located in the danger zones [3].

The complexity of conducting safe crane operations requires considerable knowledge and experience. This is why it is essential to get the appropriate training and certification for operating cranes. As noted in regulations, among many other requirements, a crane operator shall correctly use and understand the crane operation controls and loading charts [16]. Furthermore, pedestrian workers must always ensure that they are aware of their surrounding environment, incl. the cranes. In the case of a crane's presence at work, workers need to familiarise themselves with staying out of any danger zones or not finding themselves inside areas where falling loads or crane components can strike them.

2.2 Existing and modern crane safety training

A typical construction safety training includes traditional classroom teaching, on-the-job training (OJT), and on-site safety meetings [17]. Classroom information is usually presented through textbooks, slideshows, and videos and is often referred to as *passive training*. On the other hand, *active training* is referred to as company-based training because it is linked to actual work tasks learned through active participation. The *safety meetings* on-site are often weekly or even daily and are an essential part of safety training. A current challenge is how effective workers learn and how well they use their safety knowledge in practice.

As experienced in many vocational schools in construction worldwide, the individual backgrounds of apprentices intending to become certified crane operators vary widely. Teizer et al. [4] argue that the traditional methods are ineffective for some participants. This may challenge passive training effectiveness, which is often little engaging and provides limited personalized feedback. Therefore, research proposes a shift towards engaging, motivating, and efficient training methods. These ultimately can ensure that long-term hazard recollection improves workers' awareness of risks while at work [18].

Alternative methods have been investigated to improve learning outcomes for students that are more engaging and motivating. One method that has been proven to be beneficial for safety training is the use of VR. VR is a computer-generated environment where the fundamental idea is to enable participant immersion. It provides the opportunity to explore and interact with the virtual environment (VE) and its components [19]. Therefore, creating training scenarios in VE where workers can simulate feeling present on a real construction site allows them to experience hazardous situations that would otherwise be difficult or impossible to replicate in the real world.

Different display devices define the level of immersion the participant experiences. A desktop computer device with a mouse and keyboard gives the lowest degree of immersion. Head-mounted displays (HMDs), which are the most common form of displaying VEs, provide the user with a high level of immersion. If the hardware components can completely block out the real world, the user can become fully immersed in the environment and possibly achieve high illusions of presence and a high level of realism [5].

Recent game developments for entertainment have increased the use of several different display devices in one collaborative multiplayer VR environment. This is called *asymmetrical VR*. One or more players can be immersed in the same simulation with HMDs, while other players can simultaneously join through different displays such as smartphones or desktops [10]. This setup can be beneficial when there are limited VR-compatible devices as it can become quite costly to purchase multiple systems. In addition, asymmetrical VR also allows the inclusion of players who are susceptible to VR sickness.

Serious games for construction have not implemented asymmetrical VR components in the currently available VR serious games. This finding coincides with the fact that there are limited multiplayer virtual environments within the construction safety training field. However, the construction industry is greatly dependent on different professions working together, and there should be a greater focus on developing shared immersive experiences [20].

One of the first attempts to examine multiplayer environments for construction was developed by [21]. It was a VR multiplayer serious game developed to teach lean construction, with three participants interacting in a shared virtual environment while performing construction tasks in a less wasteful way.

Noteworthy to mention is also the pre-existing experiences of (some of the co-) authors with VR games for construction safety purposes. As seen in previous serious games [4, 8, 9], equipment performing lifting and transporting operations have been ‘hardcoded’ (automated) in these VE experiences. However, research is needed to prove whether or not such ‘robots in VR’ represent or get close to near-human behavior.

In addition, Golovina et al. [9] developed a VR serious game where data of the players’ paths were tracked. The data included trajectories and timestamped locations of collisions when participants were in a danger zone or collided with equipment. The data log was used for run-time or post-experience analysis. Their novel approach allows for detailed instructor-student feedback, which demonstrated to improve learning outcomes.

However, all previously mentioned serious games were single-player environments and where equipment followed predetermined paths. This could potentially lead to players getting too quickly accustomed to and predicting the machines’ pathway. Ultimately, this can eventually lower the level of realism of the user experience and adversely impact learning effectiveness.

In sum, current research gaps exist concerning safety training in virtuality utilizing the potential of multiplayer and asymmetrical VR components for creating more realistic training environments. The next paper section explains the method of developing the asymmetrical VR multiplayer scenario created to demonstrate worker exposure to overhead crane loads. An indoor environment was selected because previous research by Bükrü et al. [22] showed success in limiting the visible workspace so participants would not lose oversight.

3 Methodology

The system used for the game development takes advantage of several different hardware and software tools and the cross-platform communication between these. The software and hardware tools presented in Figure 1 were used for developing, testing, and analyzing the serious game. This figure also shows how the data communication works with a central server and all clients communicating to ensure efficient data transferring. The developed virtual environment is created for cross-platform use, meaning devices from different suppliers can be used simultaneously in the multiplayer scenario. The game engine used for the development of the serious game was Unity 3D. The virtual environment was based on an already existing multiplayer serious game developed by the co-authors Jacobsen et al. [21]. It was significantly modified to fit the purpose of this research.

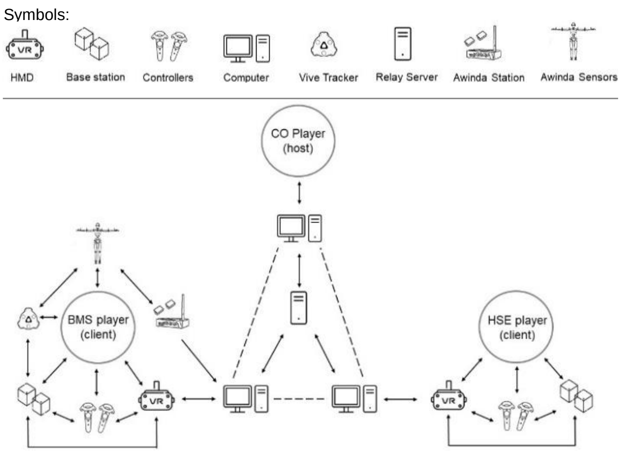

Figure 1. System architecture of the asymmetrical multiplayer virtual reality serious game.

Modifications were done by editing the scene in Unity and implementing motion data streaming from the external software MVN Analyse. Photon Unity Networking (PUN) provided the connectivity between the clients. The reason was that PUN proved successful in supporting a multiplayer environment in previous research [21]. Figure 2 shows how the developed asymmetrical multiplayer VR serious game environment that three human participants in the roles of, respectively, one worker (called BMS player), one crane operator (CO player), and one health, safety, and environment coordinator (HSE player).

Figure 2. Overview of the workspace in the asymmetrical multiplayer virtual environment.

To add complexity to the scenario, a (sometimes) moving robot on a fixed platform and a human-like robotic avatar were placed in the same scene (Figure 3).

Figure 3. Robotic arm and avatar of robotic player.

For most of the work time, the avatar was outside the safe area of the robotic arm. To make the avatar's motion most realistic to human body motions, an asset developed by Xsens was used to stream human body motion data from MVN Analyse into Unity 3D. This asset provided the opportunity of implementing a pre-recorded avatar from MVN Analyse into the Unity scene. As motion data recording was created and imported into Unity, run-time performance was not tested but is optional for implementation. This can further improve the level of realism in the scene and add more features to disrupt the players in their assigned work environment. For simplicity reasons, the pre-recorded avatar is walking between a workstation and a stationary robotic arm in the center of the warehouse to do maintenance work.

Likewise, the previously mentioned industrial robot is placed in the center of the warehouse and enriches the game scene to be more realistic and creates a task for the pre-recorded avatar to facilitate interactions with the players. An animation was made to make the robot move more realistically. In addition, there is an opening in the safety barricades on each side of the robot station. This was done to create a shortcut that the players could potentially use. This area is classified as a danger zone and should not be entered.

The gantry crane controlled by one of the participants (CO player) is installed in the ceiling and can freely be moved across the warehouse. The area underneath the moving crane hook is divided into three safety zones, a red zone, a yellow zone, and a green zone. These zones are not visible to the players.

The red zone is the most dangerous area below the crane, which is directly underneath the load. A circle defines this area with the crane hook as the center and a radius equivalent to the farthest distance to any point on the suspended load [23]. The yellow zone is defined as a danger zone underneath the crane load, an area outside the red zone with a given radius from the center of the crane hook. This radius is equal to the red zone radius with an additional clearance distance. This additional distance is usually between 1.5 and 3 meters and is decided by a safety professional, taking the surrounding environment's nature, and the crane loads characteristics into account [22]. For the experiment, it was set to 2.52 m with the possibility of changing it via a slider in Unity (Figure 4).

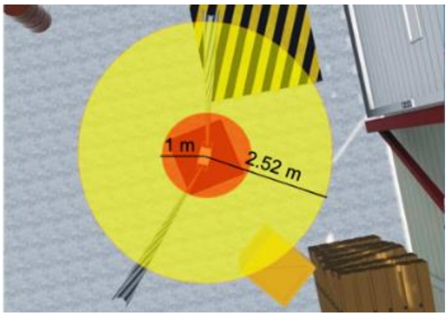

Figure 4. Two colliders associated with crane load.

If any worker enters the red or yellow zone, a warning signal is given immediately to realize the hazardous situation and take action. In this research, this is done to one of the two groups by vibrotactile haptic feedback. Finally, the green zone is defined as the area where ground workers are unlikely to get struck by falling crane load hazards [23] and therefore, no alarm is given.

4 Implementation

The VR multiplayer game environment set inside the warehouse is developed for the three players performing different tasks. Two players are immersed with HMDs and interact with the VE through controllers, whereas the third player operates the gantry crane using a computer screen and keyboard. To simplify, the players are divided into three categories: A construction worker wearing a Body Motion Suit (BMS) player, a Health Safety and Environment (HSE) player, and a Crane Operator (CO) player. Two of them were in the same room, the third one (HSE) was located in a different VR room at the research facility (Figure 4).

Figure 4. VR stations in the research facility.

01. BMS instruction board
02. HSE instruction board
03. PPE - Safety helmets
04. Placing of drywall sheets
05. Placing of toilet and sink
06. Placing of pipes (behind the wall)
07. Placing of lamps and electrical wires
08. Storage area
09. Loading zone
10. Temporary loading zone
11. Boxes for CO players' task
12. Pre-recorded avatar
13. Robot arm station

Figure 5. Components of the virtual environment indicating the work tasks and their locations.

The Body Motion Suit (BMS) player is wearing the MVN Awinda sensors and HMD with controllers. Due to limitations in game development experience, the motion data could not be used to visualize a virtual avatar. The data, however, was used for post-game analysis. The BMS player has three different tasks shown through a virtual instructions board (see #1 in Figure 5). The tasks are placing six drywall sheets (#4), installing a toilet and sink with associated pipes (#5), and placing two electrical wires and lamps (#7).

An untidy workplace with unorganized equipment, material and waste have a negative effect on safety. This, combined with poor material storage, affects where and how workers move around a construction site, thereby also which hazards they might be subjected to.

The Health, Safety and Environment (HSE) player is the other player that works inside the warehouse using the HMD and controllers. The HSE player's task is to clean up the workstation and make it safe. This includes multiple objects and equipment scattered around on the warehouse floor. Furthermore, the HSE player has to place two safety barricades (placed just under #2) around the robot arm station to secure this restricted area (#13). Pictorial instructions are given (#2) at the start of the experience. While this forces the HSE to move, (unintended) interactions with the crane load may occur.

Before starting any work, the BMS and HSE player should put on a safety helmet placed on a shelf by the instruction boards (#3). This is required, as the personal protective equipment (PPE) visualizes the workers, making it easier for the crane operator to see them.

The Crane Operator (CO) player is the only player not immersed with the HMD and instead interacts through a desktop display. The task of the CO player is to move four boxes from two loading docks (#11) to a zone in front of one of the warehouse doors (#9). The boxes must be arranged in an order given on the instructions board. Because of the specific arrangement, a temporary loading zone (#10) is implemented in the robot arm station (#13), separated (and eventually secured) by barricades to allow for the rearrangement of boxes. All other components of the virtual environment not explained are listed and visible in plan view in Figure 5.

The arrangement encourages and forces interactions among the players and their roles. For example, the BMS benefits if the HSE does a good job cleaning the workspace or shielding off the robotic arm area. Unsafe acts like players entering this area when the robotic arm is in motion are then less likely to occur.

When all the clients have joined the multiplayer scene, the players can begin their tasks. Two different test scenarios were created and tested on two groups of several rounds to determine how the players on the ground performed relative to the gantry crane and its load.

The first scene, which was tested on the first group, did not give warning signals to the players when they were within the danger zone of the crane. The second scene tested on the second group gave warning signals through vibrotactile haptic feedback. For simplicity reasons, players experience automatic vibrotactile haptic feedback as constant vibrations in the controllers.

The haptic feedback is given when a player enters the long-range distance. This warning from danger implies taking action. If the players do not take immediate action after the initial haptic feedback warning, they can find themselves inside the short-range distance. When a player enters the long-range distance or the short-range distance, their X and Y coordinates are written to a log file for further (immediate or later) analysis.

An experiment was conducted with participants that studied or worked within the construction engineering field. 18 participants were divided into two different test groups to measure a potential difference in performance when vibrotactile haptic feedback was enabled and disabled. A total of six rounds were conducted, three rounds per group, with three participants per round. Before starting, the second group participants were informed that vibrations in the controllers could occur and that the vibrations were warning signals of being in danger. However, they were not told what the cause of the danger might be. This was to avoid affecting their awareness of the overhead crane.

After the experiment, participants were asked to fill out questionnaires to evaluate the usability and user experience. The *System Usability Scale* (SUS [24] and *User Experience Questionnaire* (UEQ) [25] were used for this purpose. Due to the limited space, this is not further analyzed in this paper.

Two rooms and three computers were needed for the experiment. As explained earlier, the CO and BMS players were in the same room, and the HSE player was in another, separate room. Due to how the multiplayer scenario is developed, all players needed to be connected through different computers.

5 Data collection and analysis

The data collection was done within Unity using C# scripts, which collected X- and Y-coordinates of objects in the scene in run-time. The coordinates were collected as tracking coordinates for both the workers and crane and as collision coordinates between the workers and the crane. The tracking coordinates were collected continuously during the entire game, while the collision coordinates were collected when a player entered a predefined zone (crane danger zone or the robotic arm area of the site). The data was written to a .txt file for simplicity in further analysis. This setup was done for both players in VR. The data was imported to MATLAB and visualized to show the movements of players and crane in the scene. Furthermore, the collision coordinates visualize where the player had been in danger.

6 Results

Note that the 9 participants in the first group were given minimal information about how to implement safe behavior in the VE. Table 1 presents the comparison of the total crane collision occurrences and durations between the two groups.

Table 1. Crane load collider incidents in groups 1 and 2 (with and without haptic feedback (HF), respectively),

Group	Long-range distance (2.52 m)		Short-range distance (1 m)	
	Count [No.]	Time [s]	Count [No.]	Time [s]
1 (w/o HF)	57	314	11	35
2 (w/ HF)	47	203	11	24
Delta [%]	-17.5	-35.4	0	-31.4

A significant decrease can be seen in both duration and occurrence for the participants who received warning signals when experiencing the dangerous zone underneath the crane load. The total duration underneath the long-range distance decreased by 111 seconds (35.4%). There was a total of 10 occurrences less for group 2 (17.5% decrease). Furthermore, the total duration underneath the short-range distance decreased by 11 seconds (31.4%), while the total occurrences were the same as group 1. Figure 6 shows example illustrations from two of the participants, one belonging to each group. The plots generated automatically in Matlab® precisely document where and how frequent these incidents occurred.

It indicates that the players in group 2, who received haptic feedback, were more aware of the crane and their safety, as they had an average decrease in all parameters measured, except occurrence. Participants did not always know which direction the crane was moving. It was observed that when participants were walking, and the crane came behind them, they backed away as they assumed it was in front of them, thereby walking further into the danger zone of the crane. Yet, the change in short-range duration demonstrates how much faster the participants from the second group retreated from the hazardous area due to the shorter duration. The results suggest haptic feedback affected their safety awareness.

There were no changes seen concerning the short-range distance. The skillset of the players might be a reason. Furthermore, the results were highly dependent on the CO. Some CO players were more careful and kept to one side of the warehouse, as seen when comparing the play rounds in Figure 7. Since three computer systems needed to send information back and forth instantly, minor synchronization errors were experienced, as shown in Figure 7. Such delay leads to minor errors in the results. To avoid this from happening, all information was taken from the computer of the participant that was in focus. This means that crane trajectory data was also taken from the BMS system when analyzing the BMS player. This ensured that what the player saw was also what was used for data analysis.

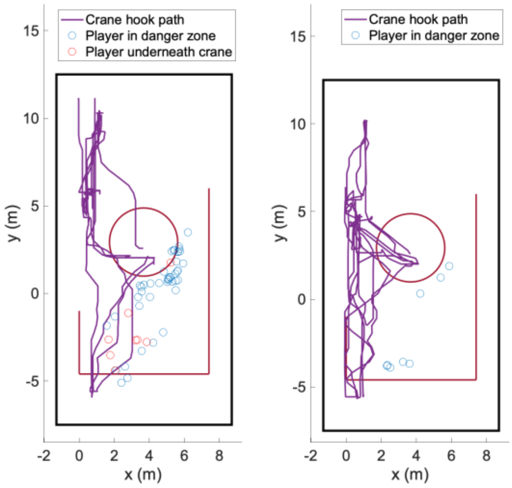

Figure 6. One sample participant of groups 1 and 2, respectively: #1.2.1 (left) and #2.3.1 (right).

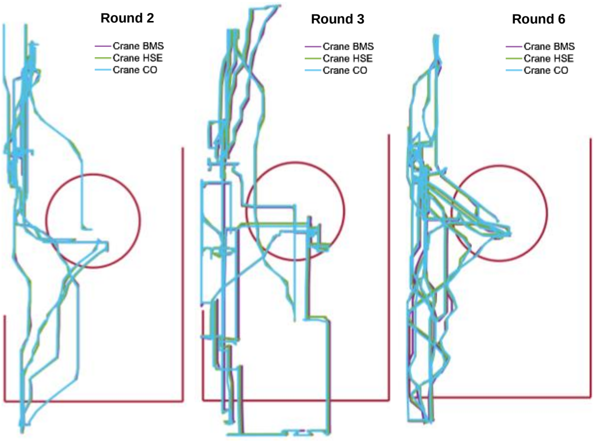

Figure 7. Slight deviations in the crane hook paths in the multiplayer asymmetrical serious game as experienced by the 3 players (BMS, HSE, and CO) in the virtual environment.

Based on the track path analysis, it was observed that all crane paths were unique and different even though the tasks were the same for all six rounds. In addition, results from the UEQ showed that the participants immersed with the HMDs experienced the scene more unpredictable than the COs. This verifies that including a human-controlled crane in a VR serious game creates more realistic paths that the other players (workers on the ground) cannot predict easily.

7 Conclusion

An asymmetrical multiplayer VR serious game was developed for the first time for construction safety training purposes. The game's novelty is that it allows players to immerse themselves in a highly dynamic virtual work environment with others via both head-mounted display and desktop display to experience safe exposure to hazards. This allows for the training to be more realistic as other participants are in the environment just as in reality. While the external player operating a gantry crane can act unsafely, such as exposing fellow players to an overhanging load, incident data is collected. Furthermore, the study quantified the effect of vibrotactile haptic feedback on safety awareness, and therefore also how this could change the behavior and safety performance of participants.

In-game data analysis and evaluations of participant user experiences indicate that both asymmetrical virtual environments and vibrotactile haptic feedback are useful in safety training. The first created unpredictable and thus more realistic interactions in the VE than existing serious games demonstrate. The second reduced the frequency and length of hazard exposure. Proven was that players with feedback also left hazards areas quicker.

Based on further findings from participants' feedback, players fully immersed in the scene experienced the scenario much more unpredictable than the players operating the crane through a desktop display. The virtual environment benefited from a human controlling the load.

Some technical limitations and that the particular serious game tested only human-machine interactions encourage further research and development, e.g.. an analysis of the usability and user experience.

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