Human Factors in Virtual Environments and Game Design, Vol. 96, 2023, 93–100
https://doi.org/10.54941/ahfe1003871

An Immersive Virtual Simulation to Assess the Effects of Engaging Tasks on Situational Safety Awareness

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ABSTRACT

Issues about industrial safety during demanding activities are of paramount importance, especially regarding accident prevention. This paper assesses the situational safety awareness (SSA) of two groups of participants in an immersive virtual space according to a task specification. The purpose was to investigate the influence of engaging work exposure on their SSA while conducting plant maintenance activities in the virtual space. The maintenance activity involved changing the engine filter of a gas-powered engine in a computer-based simulation environment. For the procedure, the virtual reality-accident causation model (VR-ACM) comprising 3-D modelling and simulation, accident scenario, and safety assessment was employed for the experiment. Two groups of participants undertook the experiment and provided simulation data and perceptual feedback for the assessment. These groups constituted; the experimental group (n=26) engaged with an air filter replacement exercise and the control group (n=26) was not given any responsibility. Questions based on the Slater-Usoh-Steed (SUS) questionnaire which accesses the three themes of *presence* was employed for measuring the SSA experienced in the virtual space. The three assessment themes include the potential to perceive hazardous conditions, comprehension of the conditions, and the ability to project lessons in the likely event of the situation arising. This measurement was to evaluate participants' perception of the virtual space, as the dominant reality rather than their actual location. Despite the substantial levels of *presence* demonstrated by both participating groups according to the results, the mean evacuation duration of those with the activity ($M = 82.42$, $SD = 18.01$) compared to those without the activity ($M = 64.58$, $SD = 18.34$) demonstrated a statistically significant difference, $t\ (52) = 3.26$, $p = .001$ in the influence of the working activity to a lesser SSA in the virtual space.

Keywords: Virtual reality, 3D simulation, Situational safety awareness, Presence, Work exposure

INTRODUCTION

Prompt recognition of a fire in a building is necessary for evacuation and possibly, for mitigating the impact of impending disasters. This is evident in one's situational awareness (SA), particularly in high-risk occupational settings. SA is an important human factor that is necessary for accident prevention, especially in situations that require prompt reactions, such as during emergency evacuations. Given the potential consequences of fire disasters and because of the associated catastrophic effects, which can threaten the existence of

an organization with unquantifiable effects on casualties, evacuations can become necessary while performing routine occupational activities such as preventive maintenance (PM) tasks. That notwithstanding, both fire emergency assessments and fire safety assessments are largely generic and fail to relate specific industrial hazards for estimating the time to realize compromised tenability (Feng et al., 2022; Kwegyir-Afful & Kantola, 2020). Furthermore, the lack of relevance to risk assessment processes at the workplace has increased industrial injuries and fatalities (Aven & Flage, 2017; Kwegyir-Afful et al., 2021). However, it is often difficult to measure this attribute directly, thus researchers usually measure SA among team members during the simulation of emergencies or acute scenarios (Markwart et al., 2019).

Evidence also suggests that the lack of realism and interactivity in conventional safety methods contributes to the low levels of employee safety behaviour (Kwegyir-Afful et al., 2017). Besides, numerous occupational health and safety standards and statutory legislations emphasize active risk assessments towards enhancing occupational safety (Sacks et al., 2013). For this reason, studies of fire generation and spread constitute a high proportion of fire safety-related research such as in gas powerhouses. Meanwhile, several empirical pieces of research indicate the potential of immersive spaces in presenting emergencies for safety situational awareness (SSA) (Kadri et al., 2014; Salmon & Plant, 2022). The impact of such exercises contributes to empowering participants for improving awareness of mental models, which is necessary during emergency safety training sections (Sacks et al., 2013).

Given the fact that it is not prudent and practical to expose people to real hazards for evacuation assessments, several evacuation tenability types of research employ safe and seemingly hazardous emergencies that do not compromise subjects' safety: - immersive virtual reality (VR) (Sacks et al., 2013). VR has been effective in this area by presenting participants with such conditions, processes and situations while isolating them from the actual hazards of the simulated scenarios. Consequently, it is to experience the related perceptions of the real situation (Kwegyir-Afful, 2021). Furthermore, state-of-the-art VR technologies can provide audio-visual sensations with haptic responses close to nature to increase realism and interactivity in simulated experiences. Besides, such exposure to VR results in the cognitive information processing that resides in the long-term memory of participants (Seo et al., 2021). The enthusiasm, realism, and involvement that subjects feel throughout an immersive encounter are what promote VR in emergency training sections, which is grounded in methods geared at measurable learning outcomes (Markwart et al., 2019). Thus, VR can provide a feasible alternative in circumstances during hazard evaluations, which are required for accident prevention. Therefore, more computer-based training sections of SSA have emerged to enhance SSA in several fields by ensuring that employees and workers are well-equipped in the likely event of hazards (Feng et al., 2022).

The current research thus aims to investigate the consequences of an engaging air filter replacement task on occupants' preparedness for evacuation before the egress routes become untenable from the raging fire effluents. It is, therefore, necessary to graphically and interactively represent and express

the fire dynamics as a realistic emergency scenario to achieve this goal. To experiment with this scenario, answers are sought for the following research questions (RQ).

RQ1: What levels of *presence* necessary for SSA assessment can be achieved in a fully immersive virtual space of a GPP simulation?

RQ2: Can an engaging task in a powerhouse simulation compromise the egress duration during a fire emergency?

To address these RQs, this study first provides an overview of the relevant literature on the engaging activity, the VR environment, and SSA followed by a description of the methodology and theoretical framework employed in the study. Next, we present the experiment procedure which describes the structure and empirical data collection and evaluation. Finally, results are discussed in light of our hypotheses as explained in the RQs. The study concludes with a retrospective look regarding the contributions and implications, as well as noting the limitations and suggestions for future research.

BACKGROUND

Air Filter Replacement Tasks

A dirty air filter reduces the performance of an internal combustion engine (ICE) by increasing consumption and reducing the engine's life span. For this reason, periodic filter replacement of an air filter on ICEs' is an important exercise for ensuring the smooth and efficient running of these engines (Yang et al., 2018). Such proactive safety measures create awareness and consciousness for preparedness in potentially dangerous situations (Yang et al., 2018).

Situational Awareness

SA within occupational safety context means one's perception of the environmental conditions through their ability to recognize potentially hazardous and risky situations before the occurrence of possible accidents (Salmon & Plant, 2022). SA is thus defined as one's ability to sustain an adequate representation of the state of the environment in a convoluted and dynamic hazardous situation. In particular, SA is relevant to situations where rapid information processing is critical, implying serious consequences for omission or wrong decisions (Salmon & Plant, 2022). The three SA levels considered in this assessment represent Level 1, awareness of potential environmental hazardous conditions, according to the SUS questionnaire guidelines. Level 2, understanding and Level 3, links to future predictions if the perceived state occurs. Some systems in a gas powerhouse can occasionally leak, and when natural gas accumulates to 5-15%, it can explode at high temperatures. Such accident possibilities enhance safety awareness and knowledge in the workforce as a necessary factor for building a solid safety culture (Aven & Flage, 2017).

Immersive Virtual Space

As previously explained, immersive VR technology can genuinely portray three-dimensional (3-D) computer representations of objects, procedures, and events for an engaging and immersive experience (Sacks et al., 2013). In industry, VR plays an important role in work process improvements as well as in enhancing the management of safety (Markwart et al., 2019).

METHODS

The experiment began with the modelling and simulation of the plant facility, which includes the plant building, three gas-powered engines, and the air-filter replacement maintenance activity. Dhalmahapatra et al.'s (2021) VR-ACM comprising 3D modelling and simulation, accident causation and safety assessment was employed for the experiment. Following this, the accident causation and finally the assessment of the SSA experienced in the virtual space.

The experimental group was tasked with replacing the filter of the gas-powered heavy-duty engine. While performing this task, an emergency fire occurred, which necessitated awareness for successful evacuation. On the other hand, the control group was not given any activity in the virtual space. Thereafter, we assessed participants' *presence* experience and the evacuation durations in the virtual realm, which is presented in Table 1 and Table 2 respectively in the results section.

The Simulation Model Development

We employed the Unreal game engine V4.2 and Fusion 360 3D integrated cloud (version 2.0.9305) designing software to enable the creation of 3D simulations of the Gas power plant model for the experiment. The simulation was powered by a computer running (Windows 10) having an intel core

Table 1. Results of the *presen*ce levels of the two groups in VR.

Factor	A ($n = 26$)		B ($n = 26$)		$\alpha = .05$	t	95% CI
	M	*SD*	*M*	*SD*			
Sensory	5.93	0.42	5.80	0.41	P = .29	1.07	[−0.141, 0.306]
Realism	6.06	0.65	5.85	0.68	P = .26	1.15	[−0.158, 0.581]
Involvement	5.94	0.47	5.59	0.61	P = .03	2.30	[−0.044, 0.166]
Control	5.83	0.32	5.70	0.47	P = .25	1.17	[−0.093, 0.352]
Distraction	6.06	0.44	5.79	0.46	P = .04	2.16	[0.019, 0.519]

Cited from (Kwegyir-Afful, E. 2022)

Table 2. Results of the egress duration of the two groups in VR.

Groups	A ($n = 26$)		B ($n = 26$)		Δ (Sec)	t	df	p
	M	*SD*	*M*	*SD*				
RSET(Sec)	82.42	18.01	64.58	18.34	17.84	3.54	50	.001

Cited from (Kwegyir-Afful, E. 2022)

i7 processing power with a GTC graphics card. Additionally, two base stations at opposite ends relayed the plant simulation, allowing participants to experience total and complete immersion via HMDs and hand controls with gesture sensors.

The exercise began in the VR environment where the assessment tasks and personal emergency evacuation plan (PEEP) were individually explained to all participants. The VR techniques related to HMDs, controllers, drills, and SSA-based questionnaires were also clarified. We further hinted that participation was totally voluntary and the participants' confidentiality was guaranteed. Implying that participants could pull out of the experiment at any time without the need for an explanation. By agreement, both the researcher and each of the participants signed an informed consent form. As a result, data was collected based on anonymity and no-tracking criteria.

The Experiment Set-Up

As explained previously, the exercises in the VR environment were performed as follows: Both participating groups were first given the task of replacing the filter on the heavy-duty engine at the factory. Unknown to the participants, the accident simulator starts after 8 min. of task operation and starts emitting thick smoke which immediately populates the facility. Participants then wore the HMD headsets. This provided a 3D view of the simulated system depending on the viewing angle. The smoke was caused by a gas leak from the facility's second engine. Participants were instructed to evacuate the facility through the door (nearest exit) upon recognition of the emergency. The simulation model intentionally omits gas alarms, and therefore fire detection was to be solely by participant awareness. The reason for this was to allow participants to visually sense the emergency from the smoke and fire, to test their SSA.

In this simulation, the emergency evacuation procedure included discovering the fire outbreak in the form of smoke and leaving the plant through the designated escape route. The first condition was classified as Group A. This was when the experimental group of participants were engaged in the task of replacing an air filter on a gas-powered engine.

Data Collection

The 52 student participants were selected from four schools (Universities) in Vaasa, Finland and the entire simulation experiment was held at the Technobothnia VR Research and Development Laboratory, Vaasa, Finland. Following the task performance as outlined above, the participants provided their responses to the questionnaire regarding the prospects of the virtual space and training for SSA. These were rated on a 7-point Likert scale categorized from 1 (totally disagree) to 7 representing totally agree.

Hypotheses: Depending on the SSA level achievable in the plant simulation according to RQ1, we posit:

H1: Substantial levels of *presence* necessary for SSA assessment can be achieved in a fully immersive virtual space. Measurements: We measured the participant's SSA level using portions of the SUSQ. As already mentioned,

this was done by determining the depth of tele*presence* and exposure based on the participant's reaction in the virtual space. Table 1 in the results section shows the data obtained for the present measurement according to the SSA.

H2: The more visually demanding a task is in a powerhouse, the greater the likelihood of compromising the egress duration during a fire emergency. The purpose of the grouping was to investigate the effect of the task activity on the SSA by measuring the difference in time from the fire occurrence and their successful evacuation from the virtual plant.

RESULTS AND DISCUSSIONS

This section reveals the results of the experiment which sought to answer RQ1 and RQ2. Particularly, RQ1 regards the *presence* levels that could be achieved for the SSA assessment in a fully immersive virtual space of a GPP simulation, and RQ2 sought to investigate the possibility of an engaging task in compromising evacuees' egress duration during a fire emergency scenario. From Table 1, group A scored a mean of 5.96, and group B achieved a mean of 5.74. According to the 7-point Likert scale, any value above 4.0 indicates agreement with the questions, while 7 represents total agreement. Obtained values for both groups in the table demonstrate appreciable levels of *presence* in the simulation which answers RQ1.

In answer to RQ2, the results in Table 2 show the mean evacuation duration of those with the activity ($M = 82.42$, $SD = 18.01$) compared to those without the activity ($M = 64.58$, $SD = 18.34$). This provides a 24.27% difference between the required safe egress time (RSET) of both groups, which also demonstrates a statistically significant difference, $t\,(52) = 3.54$, $p = .001$ in the influence of the activity to a lesser SSA necessary for prompt evacuation in the virtual space. This suggests that indeed an engaging and interactive task in a 3-D powerhouse simulation can compromise the egress duration during a fire emergency and affirms *H2*.

We recorded the evacuation time between the hazard eruption and the successful evacuation from the plant to the designated safe refuge point. Although the fire detection time and premovement timings were recorded manually for each participant, the entire evacuation time (Table 2), from fire eruption to successful evacuation was extracted from the simulation data.

Implications and Contributions

The essential contribution of this study is that it proposes a framework and successfully implements an emergency fire hazard situation for recognition and evacuation in a realistic work scenario while participants were actively engaged in a powerhouse engine filter replacement task. Besides, the exercise can enable designers of industrial facilities to estimate egress durations during emergencies. Additionally, the exercise has highlighted the possibility of the prediction of the safest evacuation route in the event of a fire breaking out in a high-risk facility. On the other hand, the exercise has highlighted the significance immersive spaces play in SSA assessments to ensure safety in the event of a fire. Besides, the experiment has shown that participants in a virtual

space can experience a level of tele*presence* necessary for experimenting in emergencies.

Although the immersive simulation's evacuation speed may be artificial, which is a common limitation of most VR simulations, however this study is extremely important because it takes advantage of the benefits of fire safety evacuations, which will help expand the use of VR for accurate safety assessments. Furthermore, studies in the field such as Seo et al. (2021) and Kadri et al. (2014) deliver impressions of 3D computer-generated simulations to the users' senses through vision, audio, and tactile features of the HMD and handheld controllers for safety assessments. The research also contributes to the utilization of VR simulations for revealing situations which cannot be deliberately experimented on, as was demonstrated by Dhalmahapatra et al. (2020).

Limitations and Future Works

In spite of the highlighted contributions, this study experienced various limitations and constraints that are important for debate, which also serve as the foundation for ongoing research in this direction. Additionally, the study did not consider a packed fire accident evacuation scenario, which typically causes numerous casualties. Secondly, our experiment did not constitute a multisensory interface, but only audio-visual sensations with a haptic response. This can be experimented in future simulations. Further research is however required to compare a VR-based evacuation and real-life evacuations to conclude the inappropriateness of conventional fire training sections where participants are ready and waiting for a fire to initiate an evacuation.

CONCLUSION

This SSA exercise has been possible through several immersive VR emergency encounters involving a wide range of student participants to provide perceptions as feedback. Specifically, the experiment firstly concludes according to our RQs that perceptible levels of *presence* required for SSA were feasible in the fully immersive virtual space of a gas powerhouse simulation. Secondly, the experiment has affirmed that engaging in maintenance activity can compromise participants' egress duration in an emergency fire situation. This was a result of the experimental group being overly engaged in a task that absorbed their visual attention.

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