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Simulation-based assessments of fire emergency preparedness and response in virtual reality

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The current study aimed at evaluating the prospects of a three-dimensional gas power plant (GPP) simulation in an immersive virtual reality (IVR) environment for fire emergency preparedness and response (EPR). To achieve this aim, the study assessed the possibility of safety situational awareness, evacuation drills and hazard mitigation exercises during a fire emergency simulation scenario. The study likewise evaluated the safety and ergonomics of the environment while addressing this aim. We employed the virtual reality accident causation model (VR-ACM) for the assessment with 54 participants individually in IVR. Participants were grouped into two according to whether they had work experience in engineering or not. The obtained results suggested that IVR can be realistic and safe, with the potential for presenting hazardous scenarios necessary for fire EPR. Furthermore, the results indicated that there were no statistically significant differences in the perceptions of both groups regarding the prospects of IVR towards EPR.

Keywords: three-dimensional simulation; fire evacuation drills; ergonomics; simulation-based; immersive virtual reality; emergency preparedness and response

1. Introduction

Several compelling findings suggest that there has been a significant reduction in accident rates and an increase in safety awareness and litigation avoidance due to active and robust occupational safety practices [1–3]. Such emergency practices play important roles by ensuring that workers and employers are well equipped and prepared during hazards [2]. For this reason, industries and safety standards regard emergency preparedness and response (EPR) key to safety countermeasures [4,5]. Evidence also implies that the absence of safety training (ST), inadequate ST or a lack of relevant EPR contributes to increasing industrial injuries and fatalities during emergencies [2,4]. This notwithstanding, exposing workers to hazardous situations in live sections can be dangerous and too costly [6]. Consequently, the status quo of EPR logically, but rarely, involves practice by doing. However, an immersive virtual reality (IVR) technology can present three-dimensional (3D) computer simulations of objects, processes and events realistically for experiential and engaging encounter. IVR thus serves as a suitable option in situations that are either too expensive or impractical for direct hazard assessments necessary for EPR [5,7,8].

Grounded in methodologies, IVR thrives on the interest, realism and enthusiasm that subjects experience during an immersive encounter [9,10]. Furthermore, IVR provides real-time experience of computer-generated environments needed in simulation-based (SB) assessments [11–13]. Coupled to this, the technology presents information retention capabilities and benefits of experiential learning that exceed traditional methods [14–16]. Besides, evidence suggests that IVR is the best currently known method for assessments regarding hazard identifications and accident reconstructions [9]. Accordingly, Dale’s theory of the learning pyramid specifies between 75 and 90% absorption and retention as subjects ‘practice by doing’ [17,18]. For this reason, research related to employee development places IVR assessments in the category of practice by doing [19]. Thus, IVR serves as a useful alternative with captivating tasks towards enhancing EPR [20,21]. For this reason, IVR is currently gaining popularity in education and industry for risk assessments, design reviews and training [12,18,22]. Despite these growing potentials, applications of EPR are confined mainly to specific high-risk industries such as construction, mining, aviation and healthcare [16,23,24].

Traditional EPR methods are limited to classroom learning, and this has disadvantages in realism and without response to interactions [16]. Such traditional methods are rather common for risk assessments in gas power plants (GPPs), where the gas system has been noted as a high fire risk [16,21]. Therefore, activities of EPR in conditions with no accidental exposure renders the practice minimally effective [2]. This study therefore targeted investigating the

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prospects of EPR in a 3D simulation of a GPP in IVR. To achieve this aim, we employed the virtual reality (VR) accident causation model (ACM), which incorporates a series of events for triggering fire outbreaks. This model was employed for designing and implementing fire EPR that constitutes situational awareness (SA), fire evacuation drills (FED) and fire hazard mitigations. We further formulated four research questions (RQs) for testing the prospects of the exercise:

- RQ1: What levels of safety SA necessary for fire hazard detection can be attained in an IVR GPP simulation?
- RQ2: How effective will an IVR simulation environment of a GPP be for EPR?
- RQ3: How safe and ergonomically viable is the IVR environment for fire EPR?
- RQ4: Are there significant differences in the results of RQ1, RQ2 and RQ3 between participants with engineering work experience and participants without any engineering work experience?

We structured the rest of the article as follows to address these questions. In the next section, the background provides an overview of the pertinent literature on IVR, FED and hazard mitigations followed by the methodology and theoretical framework related to EPR. Next, we present the conceptual model of the study that describes the structure and empirical framework of the research. Subsequently, explanations of the experiment procedure and data gathering methods are presented. Thereafter, results are presented that elaborate and discuss the research findings regarding the four hypotheses. Finally, the study concludes in retrospect with theoretical as well as practical contributions and implications while examining the study limitations and suggestions for further research.

2. Background research

Fire EPR constitutes fire hazard identification and risk assessments, and relies on the requirements of Occupational Health and Safety Management Systems (OHSMS) enshrined in Standard No. ISO 45001:2018 [25] for the prevention of accidents and safety practices [26]. For this reason, it is mandatory for an International Organization for Standardization (ISO)-certified facility to ensure that all emergency preparedness plans, training and provisions are developed and assessed continuously for the health and safety of workers, employers and visitors [26].

Factory EPR includes adequate emergency exits, as well as accessibility to the exits, stairs and walkways in preparation for exiting the facility during emergencies [27]. Coupled to these, the requisite knowledge, skill and experience for exiting a facility are vital for accident prevention and survival during emergency evacuations [22]. These are outlined as follows:

- familiarity with the environment, emergency safety procedures and exits;
- realization of situations that necessitate evacuation;
- understanding of the basic guidance during and after emergencies;
- emergency hazard mitigation procedures [7,11,26].

2.1. *Safety evacuation assessment*

Several issues require consideration when designing facilities regarding safety evacuations in EPR. Some of these are as follows:

- evacuation drills do not have to be a boring repetition of annual lectures [6,27];
- transfer of tacit safety knowledge can be a major challenge [6];
- although VR provides state-of-the-art methods for EPR, it should never completely replace traditional classroom training [16];
- despite the interesting and authentic learning outcomes that VR provides, applications for EPR in immersive environments require basic gaming skills which can be challenging to some participants [27].

2.2. *Immersive VR environments*

Complete immersion in a 3D simulation environment is possible through a stereoscopic head-mounted display (HMD) headset built with gesture and weight sensors to attain true interactivity for both virtual and constructive (VC)-type simulations [10]. Embedded in the HMD are several sensors for detecting and tracking users' orientation to enhance the immersive experience [7]. This implies that users of the VR technology can navigate from one place to another as well as manipulate objects and receive sensory (visual and auditory) feedback [19,28]. As a result, simulated 3D images, scenarios and sounds in IVR create a feeling of presence for real-time response [29]. Presence in a simulation context refers to the experience that one immersed in the virtual environment receives while physically present in another [9,29]. IVR succeeds in this manner by interacting with simulations of real-world scenarios while providing real-time learning responses [30,31]. Consequently, major industries in automobile, construction and aviation employ immersive technologies for training and risk assessment with success [10,24]. IVR and computer simulations are also useful in determining accessibility of facilities during emergencies [19], as well as for improving user ergonomics [8]. For this reason, the technology enables participants to identify hazardous situations while implementing appropriate safety countermeasures during chaotic real-life situations [6,31], thereby making it suitable for providing experiential encounter for skill enhancement [3,12]. Evidence also suggests that IVR simulations are engaging and interesting; as a result, applications provide participatory, pedagogical and behavioural learning outcomes that promote cognitive learning [10,22,23].

2.3. Simulation-based fire evacuation exercise

According to Kinateder et al. [32], three vital issues require consideration when setting up IVR exercises:

- the possibility of simulation-induced sickness (SS);
- ergonomics of the environments and gadgets;
- validation of the effectiveness of the exercises for real-life emergencies [32].

These provide a useful basis for designing and implementing IVR environments successfully for fire safety evacuation exercises [27]. Scholars have long administered the simulator sickness questionnaire (SSQ) to participants after SB experiments to determine SS [20,33,34]. Bhide [27] developed a framework for fire evacuation training using a desktop computer with the mouse and keyboard as controllers. The work employed the SSQ for evaluating the safety of the simulation environment. Obtained results indicated that participants exhibited better sustained attention and interest in the virtual realm than in the conventional classroom environment. In the same way, Rzeźniczek et al. [34] employed the SSQ for determining the levels of SS before and after a motion car simulator experiment. Likewise, Cha et al. [20] developed a VR fire simulator that displays fire dynamics based on data conversion techniques for training in fire response and rescue activities.

2.4. Presence in fire evacuation simulations

Timely evacuation procedures are important during emergencies in GPPs. This is heightened by how quickly and effectively a hazardous situation can be brought to the awareness of occupants of the plant [2]. For this reason, it is prudent to access levels of SA in immersive applications where emergency actions are required, such as in fire EPR [9]. A method widely utilized for assessing the level of presence is the Slater–Usoh–Steed questionnaire (SUSQ). The SUSQ is also frequently employed for evaluating awareness during training and risk assessments in simulation environments [7,23,35]. Interestingly, SB EPR in combating fire indicates that participants exhibit similar levels of learning in simulations to those in actual scenarios [7,36].

3. Methods

3.1. Research framework, hypotheses and assessment model

This section explains our EPR assessment model, hypotheses and research methodology, as shown in Figure 1. The model is built on a modified version of Bhide's [27] virtual 3D emergency fire evacuation training design, and also based on Dhalmahapatra et al.'s [12] VR-ACM comprising SB modelling, recognition of impending hazards and, finally, assessments. Although the ACM was originally designed for accident investigations, the VR-ACM is as suitable for assessing awareness and preparedness for fire emergencies [12,37]. Figure 1 consists of the following three parts and elaborates our study methodology:

- identification (i.e., recognition of the problem, RQs and hypotheses formulation);
- virtual environment, explaining the experiment procedure characterized by a maintenance task in IVR, accident causation, awareness of the situation, evacuation and hazard mitigation in the GPP simulation;
- evaluation of the experience, where participants answer the 15-item questionnaire regarding the exercise.

The evaluation, firstly, assesses participants' levels of SA that answer RQ1 as stated in H_1 (see Section 3.5 for details of H_1–H_4). We adapted related questions from the SUSQ that are extensively utilized in analysing SA. Next was the evaluation of H_2 in answer to RQ2, which assesses the effectiveness of FED and the hazard mitigation exercises in IVR. In this way, H_2 also evaluates the success or otherwise of the immersive exposure. The questionnaire for assessing H_2 was derived from Kirkpatrick's three-stage model for evaluations. Thirdly, RQ3 seeks to discover the safety and ergonomics (SE) of the simulation environment as stated in H_3 and relies on the SSQ for measuring VR-induced symptoms and effects (VRISE). VRISE occur if one exposed to a virtual simulation generates symptoms like motion sickness. The SSQ was designed by Kennedy et al. [38] and measures three distinct factors: nausea, oculomotor disturbance and disorientation. Notably, whereas the main hypotheses of this study (i.e., H_1, H_2 and H_3) focus essentially on SA, FED with mitigation and ergonomics, and are related to the ACM in the immersive environment, the moderator hypothesis (H_4) relies on the independent variable work experience in engineering. Therefore, H_4 evaluates the differences in answers to RQ1, RQ2 and RQ3 between participants with engineering work experience and participants without any engineering work experience.

Although literature served as the main source of information for this model, we were privileged to interview two experts in EPR about GPPs, on preparedness for emergencies and FED. Key issues obtained in the interviews highlighted gas leakage and the location of the main gas valve outside the plant. Other points gathered were the importance of early recognition of fire hazards in the assessment for possible mitigation. On the other hand, information gathered about the evacuation drills during

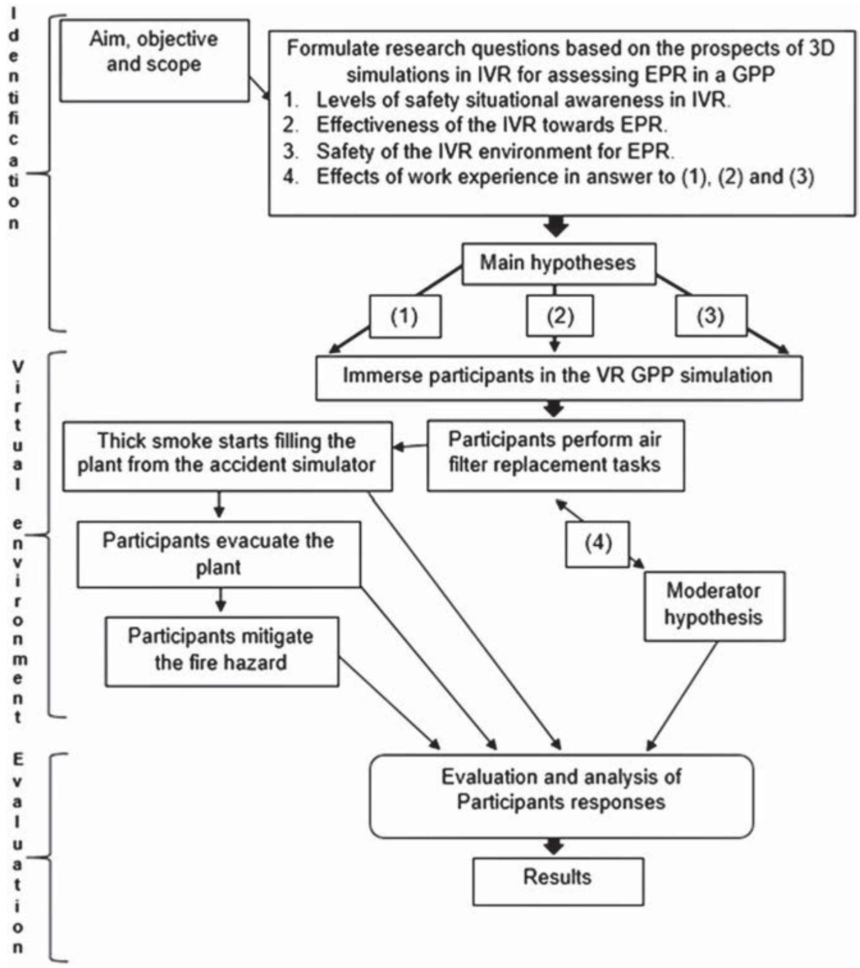

Figure 1. Conceptual model of the study.
Note: 3D = three-dimensional; EPR = emergency preparedness and response; GPP = gas power plant; IVR = immersive virtual reality; VR = virtual reality.

the interviews dealt with communicating evacuation routes precisely before the drills and keeping the emergency plan up to date as well as providing adequate evacuation routes in the plant. These interviews enabled a more practical and realistic perspective to our virtual assessment model.

3.2. *The 3D immersive environment*

We developed our model for the plant with the aid of Fusion 360 version 2.0.9305 3D designing software and Unreal real-time game engine version 4.2 (UE4) that enabled creating simulations for the assessment. A Windows 10 Enterprise, 64-bit computer (ASUS, Taiwan) with an Intel Core i7-7700 Quad-Core processor at 3.6 GHz processing speed, having a GTX 1070 graphics card, powered the simulation. Two base stations (HTC Vive, China) relayed the plant simulation for participants to experience full immersion through an HMD and hand-held controllers (HTC Vive, China) with gesture sensors. The 3D simulation environment constituted a conceptual power plant, powered by three gas-fired engines.

3.3. *Assessment procedure*

The exercise began by first explaining the IVR environment, the tasks for the assessment and the personal emergency evacuation plan (PEEP) individually to all participants and allowed questions. The explanation also covered the IVR techniques regarding the HMD, controllers and drills as well as the questionnaire based on the EPR. Participation was voluntary, and confidentiality of the participants' identity was guaranteed. Upon agreement, both researchers and participants signed the informed consent form. Consequently, we collected participants' demographic information (Table 1) based on the anonymity and non-traceability criteria. Participants then wore the HMD head set, which allows 3D views of the simulated plant depending on the angle of sight. One of the participants had to discontinue the exercise after commencement since she could not see clearly through the HMD headset without her eyeglasses. The participants were then divided into the two groups according to their work experience in the field of engineering. This was because those who work in the engineering field are usually perceived to have some

Table 1. Demographic characteristics of study participants.

Demographic factor	Value
Age	18–28 years = 37 (68.52%), 29–39 years = 13 (24.07%), 39 years and older = 4 (7.41%)
Gender	Females = 13 (24.07%), males = 41 (75.93%)
Study level	First degree = 22, master's degree = 24, PhD = 8
Work experience	Participants without engineering work experience = 21 (38.89%), participants with engineering work experience = 33 (61.11%)

occupational safety knowledge or skills that are relevant to the current exercise.

3.4. Fire evacuation and mitigation assessments

The exercise in VR proceeded as follows:

- Both groups of participants were initially tasked with replacing the air filter of the third engine in the plant.
- During the filter replacement, the accident simulator triggered dense smoke because of fire eruption, which quickly populated the plant. This smoke was caused by gas leakage from the second engine in the plant.
- Upon sensing the emergency, participants were to evacuate the plant through the nearest door exit.
- After safely exiting the plant, participants were then tasked to isolate the power source by shutting the emergency valve.

These procedures were to be implemented through the premeditated PEEP, which incorporated identification of key escape routes with specific evacuation procedures and, finally, mitigation of the impending hazard. Detection of fire was purely by the awareness of participants and the model purposefully omitted gas detectors, alarms and sirens. The reason for this was to test levels of SA at the onset of the fire hazard. The simulated smoke hazard was relevant to the awareness and preparedness for fire emergencies since smoke inhalation is attributed as the leading cause of death during fire outbreaks [11]. Secondly, early detection of gas leakage with subsequent mitigation is necessary in GPP EPR to avert the possibility of explosion. Evacuation from the plant (Figure 2) was possible with the aid of handheld controllers that enabled participants in the operating equipment to manoeuvre, walk and open doors in the plant. The second part of the assessment involved mitigation of the fire outbreak. The mitigation process involved moving outside the plant and closing the gas valve as seen in Figure 3 to stop fuelling the ignited fire.

3.5. Data collection and analysis

The 54 students who took part in the assessment were from four universities in Vaasa, Finland (Table 1). We targeted four universities to obtain a wide diversity of participants. Table 1 also presents the demographics of the participants who comprise the two groups: students without any engineering work experience; and students with some engineering work experience. The exercise took place between November 2018 and February 2020 at the Technobothnia Virtual Reality Research and Development Laboratory, which is equipped with state-of-the-art equipment needed for the exercise. After performing the task outlined in Section 3.4, participants finally evaluated the prospects of the exercise as well as the SE of the IVR environment. Assessment was obtained on a 5-point Likert scale ranging from 1 = *strongly disagree* to 5 = *strongly agree*.

3.5.1. Analysis of safety SA

SA in the context of occupational safety refers to the awareness of individuals to the surrounding conditions due to their ability in identifying potential risks and hazardous situations ahead of possible dangers [9]. Notably, SA is relevant in situations where quick information processing is vital with serious consequences for inaction or poor decisions [15]. The three levels of SA considered for this assessment, according to the SUSQ guidelines [24], constitute: level 1, perception potentials of hazardous conditions in the environment; level 2, comprehension of the condition; level 3, links to future projections in the event of the perceived condition occurring. We posit the following in answer to the levels of SA that are attainable in the plant simulation as stated in RQ1:

- H_1: substantial levels of SA necessary for fire hazard recognition are attainable in an IVR GPP simulation environment.
- Measures: we measured participants' level of SA (Q1–Q5) by portions of the SUSQ that, as aforementioned, measures and ascertains the depth of presence and exposure in virtual environments [24]. Table 3 presents the data obtained for the SA. We obtained Cronbach's $\alpha = 0.725$.

3.5.2. Assessment of the evacuation exercises

The evacuation exercise consisted of three parts; recognition, response and evacuation [7]. Participants rated their experience by their ability to evacuate from the plant from the time the fire broke out, by their ability to sense the danger and find the nearest exit for evacuation within the maximum evacuation time limit of 2.5 min as stipulated in the fire safety guides for factories and warehouses [39]. Closing the main gas valve (Figure 4) that pumps natural gas to the engine successfully halts the fire hazard and concludes the assessment. In answer to RQ2 linked to the

Figure 2. A participant evacuating the power plant at the onset of fire.

Figure 3. A participant closing the main gas valve to arrest the fire hazard.

Figure 4. Completion of the EPR assessment.
Note: EPR = emergency preparedness and response.

effectiveness of the evacuation and mitigation exercises, we hypothesize the following.

- H_2: compelling fire evacuation and mitigation exercises are feasible in IVR GPP simulations.
- Measures: to measure the effectiveness of the evacuation and mitigation drills in our questionnaire, we derived Q6–Q10 (Table 4) pursuant to Kirkpatrick's three steps for evaluating successes or otherwise of exercises. The steps are reaction (level 1), learning (level 2) and behaviour and results (level 3) [40,41]. These steps have been employed for measuring experiential learning effectively in virtual emergency evacuation exercises. We obtained Cronbach's $\alpha = 0.705$.

3.5.3. SE of the assessment environment

We combined questions of possible SS and user friendliness according to the SSQ to answer Q11–Q15. These questions, as explained earlier, consider disorientation and the oculomotor impact of VRISE as well as the ergonomics of the set-up. Oculomotor impact refers to fatigue, headache, concentration and the difficulty one encounters in focusing [23]. Besides, our simulation experiment was set up according to the health and safety instructions of the HMD safety regulatory guide in compliance with protecting the safety and well-being of participants during immersive exercises. Adhering to these regulations is essential, considering that a technology employed for assessing and promoting safety needs to ensure substantial safety levels during the assessments. For example, improper adjustment of the VR headset to a 'bad fit' on participants can lead to blurred images and poor optical presentation, which increases VRISE [15]. Secondly, it was necessary to provide supervision and adequate guidance to participants during the exercise to prevent the immediate danger posed to participants. The immersed participants are blinded to the natural environments during

Table 2. Descriptive statistics of measured variables.

Variable	Sample statistics *N*	*M*	*SD*	Minimum	Maximum
Engineering work experience	54	0.611	0.492	0	1.000
Situational awareness	54	4.226	0.485	2.200	5.000
FED/hazard mitigation	54	4.293	0.449	3.200	5.000
Safety and ergonomics	54	4.226	0.396	3.000	5.000
Overall perception	54	4.248	0.354	3.200	4.867

Note: FED = fire evacuation drills.

fully immersive exercises and this can lead to crashes or falls [42]. Thirdly, the total assessment tasks were scheduled to last less than 25 min per participant. This initiative was a measure we instituted in view of the positive correlation that exists between exposure time and VRISE [41]. The evaluation of SSQ and the ergonomics of the experiment answer RQ3, and we therefore posit:

- H_3: an IVR environment can be safe and ergonomically viable for assessing fire EPR.
- Measures: we measured any possibility of VRISE and the simulation environment ergonomics with portions of the SSQ [38]. Table 2 presents the descriptive statistics of measurements while Table 5 presents the results in answer to RQ3, which satisfies H3. We obtained Cronbach's $\alpha = 0.713$.

3.5.4. *The moderating factor 'engineering work experience'*

Whether a participant had some engineering work experience or not was the key factor employed in moderating H_1, H_2 and H_3, which correspond, respectively, to SA, FED and mitigation, and SE of the simulation environment. The difference in the responses between the two groups answers H_4. It was necessary to analyse H_4 given the general notion that work experience influences the safety response [43].

3.5.5. *Effects of engineering work experience on prospects of SB fire EPR*

It is commonly believed that engineering work experience correlates positively to safety culture and safety behaviour [4]. However, as previously noted, studies into the relationship between engineering experience and perception and the prospects of IVR towards EPR are silent. In unravelling this perception, we thus posit:

- H_4: participants with engineering work experience perceive IVR to be more beneficial for EPR than those without any engineering work experience.
- Measures: we measured the differences between the two groups by testing the independent-sample *t* test between the *M* of both groups for the three factors under consideration. This involves comparing the *M* results of H_1, H_2 and H_3, which represent SA, FED and mitigations, and SE, respectively, for both sample groups. The obtained results answers H_4. Table 6 presents the outcome.

3.6. *Assessment evaluation*

We evaluated our model by analysing the responses to the 15 items presented in Tables 3–6. These tables answer H_1–H_4 according to RQ1–RQ4, respectively. Furthermore, we computed interaction effects of the independent variable 'engineering work experience' to test the simultaneous

Table 3. Results of SA for both participating groups.

Safety situational awareness		Response to H_1: situational awareness necessary for fire hazard recognition — Without WEE ($n = 21$) *M*	*SD*	With WEE ($n = 33$) *M*	*SD*
Q1	Presence levels in the simulation	4.095	0.625	4.061	0.747
Q2	Awareness levels while working	4.286	0.644	4.364	0.859
Q3	Awareness of the plant situation	4.524	0.602	4.333	0.854
Q4	Recognition of the fire hazard	4.238	0.539	4.061	0.789
Q5	Action upon recognition of hazard	4.191	0.602	4.182	0.528
Total		4.267	0.390	4.200	0.538

Note: SA = situational awareness; WEE = work experience in engineering.

Table 4. FED and mitigation results for both groups of participants.

Evacuation drills and mitigations		Response to H_2: feasible fire evacuation and mitigation drills in IVR			
		Without WEE ($n = 21$)		With WEE ($n = 33$)	
		M	*SD*	*M*	*SD*
Q6	Personal emergency evacuation plan	4.286	0.717	4.212	0.740
Q7	Evacuation routes and signs during fire	4.333	0.483	4.182	0.846
Q8	Mitigation action to arrest the hazard	4.429	0.508	4.182	0.635
Q9	Applicability of skills to life situations	4.286	0.717	4.515	0.566
Q10	Interesting and engaging experience	4.286	0.644	4.273	0.626
Total		4.324	0.440	4.273	0.460

Note: FED = fire evacuation drills; IVR = immersive virtual reality; WEE = work experience in engineering.

Table 5. Results of SE for the two groups.

Safety and ergonomics		Response to H_3: safety/ergonomics of the immersive exercises and environment			
		Without WEE ($n = 21$)		With WEE ($n = 33$)	
		M	*SD*	*M*	*SD*
Q11	Safety of VR technology/environment	4.143	0.478	4.152	0.619
Q12	Ease of the controls/navigation in the VR	4.476	0.680	4.364	0.549
Q13	Favourable learning conditions in the VR	3.952	0.669	4.152	0.566
Q14	Feeling uncomfortable during exposure	4.238	0.539	4.303	0.637
Q15	Feeling uncomfortable after exposure	4.143	0.655	4.273	0.452
Total		4.190	0.435	4.248	0.374

Note: SE = safety and ergonomics; VR = virtual reality; WEE = work experience in engineering.

effects on the dependent variables SA, FED and mitigations, and SE. This was for the purpose of evaluating the impact of the dependent variables on the independent variables [44]. We further computed the independent variables in two successive steps to control possible confusing effects. During evaluation, answers to Q14 and Q15 in Table 5 were reverse coded due to the negative connotation present in the question format. SAS EG version 7.1 was utilized in performing the analysis for both population groups. To ascertain the significance of *M* values in Table 6, we employed a 95% confidence interval according to Cox and Lewis [45] throughout our analysis.

4. Results

This section presents the results of the three assessments as provided by the participants, which answer RQ1–RQ3 as hypothesized by H_1–H_3, respectively, and are moderated by RQ4 for H_4. These results are presented in Tables 2–5, which present the measured average values of responses for identifying the central position within each group of answers. Next, four independent-sample *t* tests were conducted to determine the similarities between the results of participants with some work experience and participants without any work experience, which answers RQ4, as presented in Table 6.

Table 6. Results of independent-sample *t* tests between variables.

Variable	*M* of WEE	*M* of no WEE	Mdn	95% confidence interval	*t*	*df*	*p*
SA	4.200	4.267	0.067	[−0.207, 0.340]	0.489	52	0.627
FED	4.273	4.324	0.051	[−0.203, 0.308]	0.404	52	0.688
SE	4.248	4.190	0.058	[−0.281, 0.166]	−0.521	52	0.605
MOP	4.240	4.26	0.02	[−0.180, 0.220]	0.199	52	0.843

Note: FED = fire evacuation drills; Mdn = median; MOP = mean overall perception; SA = situational awareness; SE = safety and ergonomics; WEE = work experience in engineering.

4.1. *Descriptive statistics*

Table 2 presents the combined results for both groups regarding the M and SD of the empirical ranges for the key study variables of all 54 participants. The table also presents the results of the general impression of all respondents to the entire assessment at the overall M perception row. We achieved a measure of reliability in internal consistency of 0.706.

4.2. *Responses to the levels of SA*

Table 3 presents the levels of SA in the immersive environment according to the SUSQ, which also elaborates the individual questions for SA and answers H_1. We also computed participants' preferences according to the Likert-scale items in percentages due to the low number of participants. Overall, 90.74% of responses from both groups combined scored 'strongly agree' or 'agree' to the questions according to Table 3. Only 1.85% of the responses registered 'strongly disagree' or 'disagree', and 7.41% were undecided regarding the question which answers H_1.

4.3. *Results of FED and mitigations*

The results of the questions pursuant to the effectiveness of FED and mitigation drills for both groups of participants are presented in Table 4. These questions concerned participants' interest, skill and knowledge acquired, which synchronizes to Kirkpatrick's three steps for evaluations and answers RQ2. The total responses of both groups to the questions presented in Table 3 and Table 4 represent the overall success or otherwise of the assessment regarding the effectiveness of IVR for EPR. The analysis of the results from Table 4 according to the independent-sample t test produced results of 0.404 with $p = 0.688$ (Table 6) for answering RQ4.

4.4. *Results of SE in IVR*

The results obtained from the questions related to SE according to H_3 answers RQ3, and Table 5 elaborates the SE of the entire IVR exercise. In this case, the results present findings on whether the simulation environment was safe for EPR. Specifically, Table 5 presents participants' perception of SS because of VRISE. This perception, as explained earlier in Section 3, assessed the three general categories of VRISE from the SSQ with the ergonomics of IVR.

4.5. *Work experience in engineering on prospects of SB fire ST*

Regarding H_4, which purports that participants' work experience in engineering affects their perception of the prospects of IVR for EPR, we conducted an independent-sample t test on all three dependent variables – i.e., SA, FED and mitigation, and SE – based on the independent variable 'work experience in engineering'. This analysis measures M of both groups for the three dependent variables to determine whether evidence exists to suggest any significant differences between the perceptions of participating groups. We obtained the individual values of the three factors as presented in Table 6, with an overall $p = 0.843$ at a significant α level of 0.05.

5. Discussion

5.1. *Examination of the obtained results*

This section explains the results presented in Section 4 regarding the effectiveness of the IVR simulation environment for SA, preparedness and response for fire emergencies, and the possible effect of engineering work experience on the examined factors. These were investigated as SA, FED and mitigation, and SE during the assessment. The obtained results individually indicated that the main ingredients of a fire EPR plan – safety awareness, safety knowledge and safety mitigation skills – can be mimicked in a real-time IVR simulation environment for improving plant safety.

5.1.1. *SA analysis in IVR*

Referring to the results presented in Table 3 that answer RQ1 about feasible levels of SA necessary for fire detection, the overall M of 4.267 (from $1 =$ *poor* to $5 =$ *excellent*) implies that a high level of SA was experienced during the immersive encounter by both participating groups. These values do not also vary greatly from M according to the obtained total SD of 0.390 and 0.538, respectively, for both groups. This implies an appreciable level of agreement amongst participants, and also reflects significant comprehension between time and space for participants during the immersive experience, which affirms H_1, in answer to RQ1, that substantial levels of SA necessary for fire detection can be attained through a 3D simulation of a GPP in an IVR environment. SA was assessed based on the underlining factors of perception, comprehension and projection. These three factors are the main ingredient that the SUSQ assesses. The results also suggest that the plant simulation set-up provides an enabling environment for assessing risks and for recognizing hazards in the intended plant design. Besides, these results conform to previous findings in the field by, e.g., Slater et al. [33], who employed the SUSQ to analyse the relationship that exists between physiological responses and breaks in the presence of 20 participants and found a significant difference between the experimental phase and the actual training. Similarly, Giglioli et al. [23] compared the sense of presence and performance with the SUSQ for subjects in an ecological task, while Lee Chang et al. [9] likewise analysed the impact of simulation against lectures for training by employing the presence tool. This suggests that IVR is feasible for SA and therefore applicable for EPR in a plant simulation. Such assessments are critical for ensuring safety in high-risk fire-prone facilities. The exercise has also enabled participants to understand the importance of emergency preparedness, for maintaining high safety awareness of one's working environment. Implications are that IVR can present 3D simulations realistically for experiencing hazardous situations necessary for EPR. Such situations make it possible to act accordingly and receive real-time response for learning, which hitherto was not possible with traditional classroom methods for comprehending SA during risk assessments.

5.1.2. *Analysis of FED and the mitigation exercises*

The results for H_2 with respect to RQ2 concerning the effectiveness of FED and the mitigation drills also indicate a positive trend. Primarily, the combined high M of 4.293 realized in Table 2 for both groups as well as the total M values of 4.324 and 4.273 presented in Table 4, according to the Likert scale from 1 to 5 based on Kirkpatrick's evaluation model, significantly indicate a positive trend. This suggests that the immersive environment can be effective for FED and mitigation, which thus confidently accepts and affirms H_2. The results also revealed that participants received full experience of close to real scenarios in a safe and controlled environment without any distractions while immersed. Besides, the exercise has demonstrated that simulating a real plant fire hazard with immediate feedback for realizing the consequences of following or not following safety procedures provides the platform necessary for experiential learning. This implies that specific hazardous scenarios can be simulated for more critical IVR safety assessments before definitive construction of the intended facility. Moreover, the combined responses register that the immersive experience offers participants the privilege to prove their knowledge at the onset of a fire emergency and receive instant feedback. Furthermore, the immersive encounter has exposed participants to the need of preparedness for decisive actions during a fire emergency. These results are also consistent with research that employs IVR towards FED and mitigation, e.g., Smith and Ericson [36], Tian et al. [40], Torda [35], Patel and Dennick [46] and Lee Chang et al. [9].

5.1.3. *SE assessment of the IVR environment*

This section explains the results obtained while assessing the SE of the IVR environment for EPR. Regarding the possibilities of VRISE, which answers RQ3, the M values of 4.190 and 4.248 obtained for both participating groups according to the SSQ results presented in Table 5 suggest appreciable levels of safety and ergonomic viability experienced by participants during the immersive exercise. These values were likewise obtained with the 5-point Likert scale as was employed in assessing responses to RQ1 and RQ2. The values advocate participants' perception, which affirms H_3 that the immersive environment provided safe conditions with negligible effects of SS, usually present in VRISE, and therefore is suitable for fire EPR. It is also necessary to explain that the high values obtained from participants presented in Table 5, regarding the safety of the VR environment, were partly due to the safety measures employed in the experiment.

The following explains the measures in accordance with the safety and regulatory guidance (HTC Vive, China) for the HMD headset [47]. Firstly, we adhered to the minimum age of 18 years during our inclusion criteria, purposefully to prevented possibilities of seizures, which according to the manual are a factor common in children [47]. Secondly, a virtual translucent wall in the immersion served as a guide to participants despite the physical guidance researchers provided for each participant throughout the exercise. This inherent feature in the HMD set-up is a safety guide for informing users of the safe area, in the actual world, to prevent the possibility of falling or crashing into an object. Thirdly, we ensured that the HMD was secured comfortably on each participant before running the simulation. This was to prevent poor optical presentation and blurred images since both factors increase SS. Similarly, we prevented hearing discomfort or loss by keeping the volume of the earpiece moderate, considering that listening to loud sounds for a long time can damage the ear. We also limited the total exposure time to 25 min according to the HTC factory-recommended exposure time of less than 30 min per immersion with a 10-min break if needed [47]. Additionally, we ensured that the headset was cleaned by sanitizing after every immersion, considering that the HMD is usually worn tightly on the user's scalp. Adhering to these safety measures contributed to increasing the safety and eliminating the health and risks potentials of the IVR environment. It was interesting to note that, apart from one participant who had to pull out of the assessment due to an eyeglasses issue, the remaining 54 participants completed the assessment successfully. This, coupled with their tabulated responses, indicates that there were no substantive symptoms such as fatigue, nausea, drowsiness, increased salivation, visual abnormalities like eye strain and double vision or any symptoms similar to motion sickness.

5.1.4. *Effects of engineering work experience*

This section explains the results obtained for RQ4, which sought to compare the results between the two participating groups. To achieve this, we compared the M of SA, FED and mitigation, and SE representing H_1, H_2 and H_3, respectively, for both groups to determine any significant differences between their perceptions. For the SA, since $p = 0.6272$ (Table 6) is greater than $\alpha = 0.05$, we can conclude that no differences exist between the perceptions of both groups regarding SA. Secondly, the results obtained for FED and mitigation provided $p = 0.688$, which is equally greater than $\alpha = 0.05$. This contrast also signifies no compelling differences between the two groups regarding answers to RQ2. Considering the results of SE, which answer RQ3, the obtained $p = 0.605$ in Table 6 is also greater than the significance $\alpha = 0.05$. This also indicates that no statistical differences exist between the perception of both groups to the levels of SE. Likewise, the overall M perception of the combined responses of all three RQs, which answers RQ4, according to H_4, shows $p = 0.843$ which is much greater than the significance $\alpha = 0.05$. We can therefore conclude that there are no significant differences in the perception between the two groups for all three factors under consideration. In this vein, H_4, which purports that work experience in engineering affects the perception of the prospects of IVR for EPR, lacks substance and we can therefore confidently reject that notion. However, these similarities signify that the application of 3D simulation in IVR for EPR is not only suitable for those who have prior safety engineering exposure, but is equally suitable for novices.

5.2. *Results validity*

We employed a purification process to check the construct validity of our results. Secondly, our data have undergone other purification processes comprising three stages:

- A check on the convergent validity; this was met since p values for all items presented in Table 6 were always high and significant. Besides, the standard errors of these items were relatively low.
- A check on discriminant validity based on the examined 95% confidence interval for each pair of constructs did not include 1.00 at any instant, as Anderson and Gerbing [48] explain.
- We verified the construct reliability, which was satisfactory as all constructs evaluated exhibited Cronbach's α greater than 0.70. Collectively, the combined results demonstrate that common method bias was unlikely to be a cause for concern in the current study.

Furthermore, the results for H_1, H_2 and H_3 are consistent with IVR simulation in related research works, e.g., Bilotta et al. [49] Bhide [27] and Nedel et al. [28], all of whom discovered that participants perceive SB fire evacuations in immersive environments positively. Likewise, Rzeźniczek et al. [34] and Borrego et al. [37] produced appreciable values when evaluating the effects of VRISE during assessments by administering the SSQ.

5.3. *Limitations of the study*

This study has some limitations worth noting. As a latitudinal study, the research did not test participants' retention of lessons over any period. Several studies, e.g., Berg and Vance [29], Bilotta et al. [49], Lee Chang et al. [9] and Cha et al. [20], however, have conducted such longitudinal studies and there is therefore ample literature to support the superiority of participants' retention in the IVR environment over conventional classroom methods. Another limitation was that the detection of the fire hazard in the form of gas leakage that caused smoke in the simulation was possible only by sight and not by smell, and therefore has the potential to limit SA in the IVR environment. Besides, the plant simulation eliminated some dynamic automated processes in an actual GPP that were not relevant to this assessment but could affect the overall plant EPR. Next, participants were able to move superficially in the plant simulation during evacuations by hurdling over objects and stairs as well as jumping from the first floor to the ground floor in seconds. This is a practice that is not feasible in reality. Despite these limitations, the study nonetheless offers valuable contributions for enhancing applications of IVR towards industrial fire EPR practices.

5.4. *Contributions and implications*

The study contributes practically and theoretically towards EPR in several ways:

- The study has demonstrated that participants in an IVR encounter of a 3D simulation environment can experience real-time emergency scenarios for safety preparedness and response at the factory conceptual stages. This is possible anywhere away from the location of the intended facility.
- By providing proactive emergency and realistic scenarios, with engaging and interesting fire encounter, the study adds to research findings regarding IVR environments for enabling adequate preparedness and planning, which helps promote factory safety measures.
- Specifically, the study demonstrates the importance of safety SA for survival during plant fire emergencies. This underpins the essence of awareness of immediate threats even when engaged in factory demanding tasks.
- To the evolving scientific literature concerning the utilization of IVR for fire emergency awareness and response, the study demonstrates that realistic situations and environments are possible, and can therefore influence safety designs at the factory conceptual stages.
- Likewise, the study contributes to the prospects of SB risk assessments as well as plant hazard identifications that are both key to EPR. According to Standard No. ISO 9001:2015 [50] and Standard No. ISO 45001:2018 [25], EPR ought to continuously improve for the purposes of promoting plant safety countermeasures [26]. We are therefore confident

that the findings presented in the experiment will spur detailed research in this direction.

Despite these potentials, and in view of the numerous limitations, however, the study does not propose that the application of IVR for fire EPR should be a complete alternative to the status quo of fire safety assessments. Rather, it should serve as a complement to traditional EPR assessments.

6. Conclusions

A VR-based fire emergency simulator has been developed and utilized in assessing the prospects of IVR for fire EPR. The model presents real-time 3D images, processes and interactivity necessary for experimentations during fire emergencies. The assessment constituted the following:

- safety SA, which studied the capacity of the immersive environment in presenting realistic hazards regarding the perception, comprehension and interpretation of a fire emergency;
- FED and mitigations, which assessed the viability of the immersive environment for EPR;
- SE of the IVR plant simulation environment.

The main purpose of the study was to examine the suitability of IVR for EPR. Two groups participated in the assessment: student participants with no engineering work experience; and student participants with some work experience in engineering. The reason for these groups was to analyse any differences in opinion for the three factors necessary for EPR. Results of the assessment revealed that, indeed, substantial levels of SA necessary for fire hazard identifications were feasible in IVR. This was because participants experienced appreciable levels of presence, interactivity and fire hazard mitigation during the assessment while immersed. Thus, our results conclude that the IVR technology is capable and suitable for revealing details of a plant design with the necessary dynamisms for fire EPR. Our experiment, notwithstanding, revealed no significant differences between perceptions of the two participating groups, which implies that the immersive technology is suitable for both groups equally for assessing EPR. The study also confirmed that a simulation environment can be safe and ergonomically suitable for fire emergency assessment provided the VR equipment, safety instructions, protocols and safety procedures are adhered to.

6.1. *Suggestions for future research*

In the future, we hope to extend a fully immersive VR-ACM for risk assessments and hazard mitigations in areas where the technology is lacking. We also hope to train two groups of participants in a prospective cohort study – one group in an actual factory and the other group in an immersive virtual environment of the same factory simulation – and verify the differences in safety culture immediately after training and over a period. The results will enable us to verify the applicability of the technology for more safety-related practices.

Disclosure statement

No potential conflict of interest was reported by the authors.

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