International Journal of Disaster Risk Reduction 67 (2022) 102681

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Effects of an engaging maintenance task on fire evacuation delays and presence in virtual reality

Ebo Kwegyir-Afful

University of Vaasa, Wolffintie 34, 65200, Vaasa, Finland

ARTICLE INFO

Keywords:
Fire evacuation
Safety
Pre-movement time
3D simulation
Virtual reality
Presence

ABSTRACT

The current study aims to investigate the capability of occupants of a powerhouse simulation to sense a fire and initiate evacuation while engaged with a task. For this reason, the study involved the maintenance task of replacing the air filter of a gas-powered engine through a series of instructions. The virtual reality-based accident causation model (VR-ACM) consisting of 3D modeling and simulation, accident causation, and safety training was adapted to address the study's aims. Two groups of participants were immersed in the virtual realm as occupants of the powerhouse to determine the pre-movement time and the evacuation duration under distinct scenarios. The first scenario constituted the experimental group ($n = 26$), who were assigned to replace the filters, while the second scenario (control $n = 26$) performed no task before the fire outbreak. An independent samples *t*-test revealed a significant difference in the pre-movement time of the groups, which suggested a decline in the perception of the experimental group due to the task. Further assessment revealed a consequential transfer of the delay at the pre-movement phase to the evacuation delay of the experimental group from the powerhouse. Secondly, the differences in *interactivity* implied that the experimental group exhibited a higher level of *involvement* and *distraction* in the *Presence* measurement than the control group. To this end, a virtual reality (VR) environment's performance and real-time functionality during a maintenance task simulation have been experimented with in an emergency fire evacuation scenario to ascertain safety concerns.

1. Introduction

Natural gas-fired powerplants are essential power solutions that contribute to a quarter of the world's electrical power supply [1]. However, the operation and maintenance of such powerhouses are inherently hazardous due to the possibility of leaking high-temperature gases or harmful gases that can cause a fire outbreak or asphyxiation, respectively [1,2]. Therefore, incorporating adequate safety measures and standards is critical in designing powerhouses to promote safety [3]. Despite such efforts, fires still occur. Accordingly, early recognition by occupants for evacuation is an essential component in *performance-based fire safety engineering designs* to protect people, property, and the environment from fire [4].

Moreover, incident assessments focusing on evacuations during fires suggest a correlation between delayed evacuation and fatality rates [5,6]. Furthermore, evidence from actual fire evacuations indicates that people are often engaged in non-evacuation tasks during fire emergencies. For example, some people gather personal belongings, talk with others, and seek information before initiating evacuation [7,8]. Other studies also affirm that the psychological reaction of evacuees before evacuation can affect the evacuation duration [8]. For these reasons, the importance of frequent evacuation drills and risk assessments in high-risk facilities has never been over-emphasized [1].

E-mail address: ebo.kwegyir-Afful@uwasa.fi.

https://doi.org/10.1016/j.ijdrr.2021.102681
Received 14 May 2021; Received in revised form 2 November 2021; Accepted 6 November 2021
Available online 10 November 2021

Against this background, and since it is unethical and unjustifiable to directly subject humans to fire effluents for estimating the duration of compromised tenability, the status quo of traditional fire evacuation drills do not involve actual fire emergencies. This renders such safety evacuation sections monotonous, uninteresting, and minimally effective [2,9,10]. Secondly, it is not prudent to measure the evacuation tenability due to an occupational task during actual fires [5]. Thirdly, information gathered from firefighters does not consider functions that have no direct effect on the courses of the fires [6]. Therefore, the established methodology for evaluating the safe time on occupant pre-movement has not been validated experimentally [9,11]. However, the enthusiasm and realism virtual reality (VR) generates during immersion coupled to the possibility of exposing participants to a safe virtual fire encounter at diverse locations and at multiple times provide a suitable means for measuring the time at which compromised tenability may occur [2,12,13]. For this reason, there has been growing interest with evidential progress in applications of VR simulations for risk assessments and skill enhancement in fire evacuations, awareness, and preparedness for fire emergencies. For example, Markwart et al. (2019) [14], Cao et al. (2019) [15], and Zhou et al. (2020) [16] experimented with evacuees' behavior during way-finding in VR. Other VR-related studies involved crowd congestion amid fire evacuations by Wang et al. (2021) [17], route turning on evacuation performance, Zhang et al. (2021) [18], and Kwegyir-Afful et al.'s (2021) fire emergency preparedness, response, and mitigation [2]. Furthermore, measuring the level of *Presence* in a virtual realm for participant-related experiments is necessary to assess the simulation's logical (face) validity [19]. Accordingly, various studies, for example, Zou et al. (2017) [20] and Kritikos et al. (2020) [21], have established that engaging participants in emergency evacuations increase their perception of *Presence* in the virtual environment.

However, there has been no attempt to investigate the impact of an engaging occupational task before an emergency fire to assess the pre-movement time due to the task in the context of VR simulations. This gap also explains why there has been no research on *Presence* measurement while performing a maintenance task in a VR simulation before a disaster. Exploring this area can serve as a platform for further assessment of VR for training in safety awareness and prompt evacuations during emergencies while engaged in demanding occupational tasks. Moreover, research in this direction would also highlight the need for further VR studies regarding emergency preparedness and egress tenability at the factory conceptual stages.

The current study thus simulates a gas powerhouse for occupants to replace air filters on an engine and firstly evaluates the effects of a maintenance task on occupants' pre-movement time when a virtual fire emergency occurs. Additionally, we assessed the overall evacuation duration of occupants in the powerhouse simulation to understand whether the pre-movement delay subsequently affected the evacuation duration. Secondly, the research assesses *Presence* due to the maintenance task amidst the emergency evacuation to determine the level of *realism* experienced by the participants in the fire simulation due to the task. The research was conducted according to the virtual reality-based accident causation model (VR-ACM) to improve accidents' safety [10]. Therefore, we seek answers to the following research questions (RQ) to satisfy the aims of the experiment.

- RQ1: What is the effect of an engaging maintenance task on the pre-movement time in a powerhouse simulation when a virtual emergency fire occurs that necessitates evacuation in VR?
- RQ2: How does the maintenance task ahead of the evacuation increase the level of *Presence* experienced in the simulation?

The article is organized as follows to address our RQs. The following section presents the background, which elaborates on the related literature to the aims and objectives of the study. After that, the methodology describes the conceptual framework of the experiment, data collection, and analysis methods employed. The results section follows, which reports the obtained data in answer to our RQs. From there on, the discussion section follows with explanations of the results and the contributions and implications. Furthermore, the limitations and future works are also tackled in the discussion section. Finally, the study concludes in retrospect, emphasizing the importance of VR in assessing emergency fire evacuations at the plant conceptual stages.

2. Background

This section discusses the pertinent literature related to VR applications for fire evacuation and the concept of *Presence* in VR for reality evaluation in a VR experiment. Other parts of this section also relate to the pre-movement time of a facility and the evacuation duration during fire emergencies.

2.1. VR fire emergency evacuations

Advances in VR technology in mimicking real situations in virtual environments for real-time assessments and feedback have proven helpful for building skills during fire safety training, fire emergency evacuations, and emergency fire preparedness [10]. For example, while assessing human behavior during an emergency fire situation, Kinateder et al. (2014) emphasized the suitability of VR as a laboratory tool for improving fire safety, despite the ergonomic and technical limitations acknowledged in the research [22]. Similarly, while investigating the ecological validity of a VR experiment, Zou et al. (2017) establish that emotional valence and emotional arousal are necessary ingredients for determining the comprehensive level of the ecological validity of a VR evacuation experiment [20]. Furthermore, in a more comprehensive VR simulation, Shaw et al. (2019) investigated human behavior in an emergency fire scenario with the regular audio-visual VR devices compared to a multisensory condition incorporating thermal and olfactory senses [7]. The results revealed the significance of VR in fire emergencies with emphasis on the added benefit of multisensory virtual environments. In another study, Zhou et al. (2020) proposed a virtual environment for safety procedures (VESPRO) in a multi-semantic fire evacuation scenario that incorporates scene-related semantics besides the building geometrics [16]. Their simulation thus included the dynamics of the fire parameters, path accessibility, and path recognition for training. Kwegyir-Afful et al. (2021) echoed this in a VR fire accident causation experiment of a gas power plant (GPP) simulation for fire evacuation drills and fire mitigations and safety and ergonomics of the virtual environment. Their investigations revealed that a VR simulation environment could be ergonomically safe with negligible cyber sicknesses for safety assessment and fire emergency preparedness and response [2]. Other studies, for example, Wang et al. (2021) [17], analyzed the effects of several evacuation parameters in an underground commercial building and discovered that crowd congestion affects the evacuation duration when the number of evacuees increases by 50 [17]. Furthermore, Zhang et al. (2021) [18] also investigated the effects of route turning on evacuees during a fire emergency in VR. They detected that the turning angle during fire evacuation significantly affects evacuees' recognition and compliance to emergency signs [18]. VR evacuation simulations have also influenced changes to the design of emergency evacuation signs on buildings. For example, Tang et al. (2009) compared different types of emergency exit signage for evacuation duration and way-finding. They detected that the type of signs affects the period of way-finding during a fire emergency [23].

Few studies in VR have tacked the effects of a task before an emergency fire evacuation. For example, Cao et al. (2019) designed a VR study to examine participants' performance during a fire emergency. Their study incorporated the task of searching for the keys to a hidden treasure when a crisis ensued. As a way findings simulation, the results indicated that the experimental group who experienced the fire spent a long time finding the museum's exit than the control group who experienced no fire emergency [15]. Although their research is relevant, the emphasis was on the effects of the fire during the evacuation and not the treasure hunting task. This bolsters the earlier explained importance of the current study regarding the experimentation of an occupational task on evacuation before a fire emergency.

2.2. The concept of presence in a virtual environment

Telepresence, which is the shortcut for *Presence*, can be defined as the experience of being in a real environment even when one is in a virtual simulation [24]. The WS *Presence* questionnaire is usually cited in academic cycles for measuring the extent to which the simulation became the dominant reality in the virtual realm [19,21]. Kritikos et al. (2020) [21] modified and categorized the *Presence* questionnaire into four moderately related domains. These are interaction, visual aspects, subjective factors, and consistency with the natural world [21]. They investigated five elements in the virtual environment, and these made up the 21-item questionnaire which eliminated sound measurements since that was not a factor under consideration in their study. The current research adopted this version of the WS questionnaire with these factors: *Sensory fidelity, realism, involvement, control,* and the *distraction* factor as proposed by Kritikos et al. (2020) [21], which are explained as:

- *Sensory factor*: This factor measures the degree of movement in the VR environment that participants experience.
- *Realism factor*: *Realism* measures how close to reality participants perceive the scenes and structures in the VR environment.
- *Involvement quality factor*: This assesses the quality of the visual display and controllers on participants while performing the task and evacuation activities.
- *Control factor*: This factor measures the perception of participants' ability to control elements within the VR environment.
- *Distraction factor*: The distraction factor measures the ease of adaptation to the VR environment.

[21,24,25].

2.3. Fire evacuation preparedness

According to the FM *Global property loss prevention data sheets*, fire outbreaks in powerhouses costs an average of $24 million [26]. Despite these financial losses, the safety of those working in such facilities is paramount. Smoke from fires spreads quickly by reducing visibility, increasing the difficulty of finding the exit [27]. Furthermore, the natural gas that feeds the engines in powerhouses, being: Methane, 0.96%, Ethane 0.02%, and Nitrogen 0.02%, produces a highly explosive mixture [28]. These, in combination with compressed air, produce fires that power the engines to have electric power. Such a system can easily ignite and burn with devastating consequences. For example, six people lost their lives in a gas powerplant in 2010 at the Kleen Energy Systems Power Station, Connecticut, during a natural gas purging process [29]. Similarly, several people got injured with one casualty during a fire outbreak at the Mytishchi gas-fired power station near Moscow in 2019 [2]. To limit and prevent these occurrences, pre-movement duration assessments of gas powerplants during regular occupational tasks at the designing stages are necessary and bolsters the relevance of the current research.

2.4. Emergency evacuation timeline

Research indicates that estimating the means of emergency egress during fires in buildings plays a critical role in evacuation preparedness [2,6]. The emergency egress system performance of a facility uses two factors for evaluation. These are the available safe egress time (ASET) and the required safe egress time (RSET) [11,30]. The ASET is the maximum time between a fire outbreak until the conditions in the enclosed facility no longer become favorable for human occupancy. The RSET is the time interval between the ignition of fire until the occupants of the enclosed facility have completely evacuated [6]. The RSET comprises the detection time, premovement time and, traveling time of the most remote occupant of a building [9,30]. The fire detection time is the duration of the ignition of a fire until the triggering of the alarming devices installed within the premises. The pre-movement time is sometimes referred to as the pre-evacuation time [9,31]. The traveling (movement) time is the duration required for occupants of a building under threat to physically move and arrive at a place of safety [32]. The movement time depends on:

- The walking speed of occupants.
- The conditions of the occupants in the building during the fire.
- The number and width of fire exits/escape routes, and

- The location of the escape route.

2.5. Evaluating the pre-movement time

The pre-movement time in a performance-based fire evacuation design plays a salient role for safe evacuation during fire emergencies, for it is at this time when evacuees recognize the fire and respond appropriately and in time (Fig. 1). For this reason, the pre-movement time plays a crucial role in evacuation successes, especially during fires [27,32]. It constitutes; recognition of the fire emergency, decision to initiate evacuation or not, information to others or seeking further details of the hazard, and finally, the response time. According to research, the majority of the people who are adversely affected during fire emergencies are those who delay the pre-movement response time [27]. Fig. 1 below demonstrates the relationship of the pre-movement time in the emergency evacuation timeline.

3. Methods

3.1. Study design and experiment setup

This section explains the study design according to the conceptual model (Fig. 2), which relies on a modified version of Dhalmahapatra et al.'s (2020) VR-ACM [10]. As noted earlier, this model comprises 3D modeling and simulation, accident causation, and safety training. However, the current model substituted the safety training with evacuation drills while performing a specific task to investigate the effects on the pre-movement time during the evacuation. The tenability limits for safe evacuation from the powerhouse were:

- The minimum visibility during the evacuation was to be above 18 m, which is the maximum distance from the remotest location in the powerhouse to any of the four exits (Fig. 4).

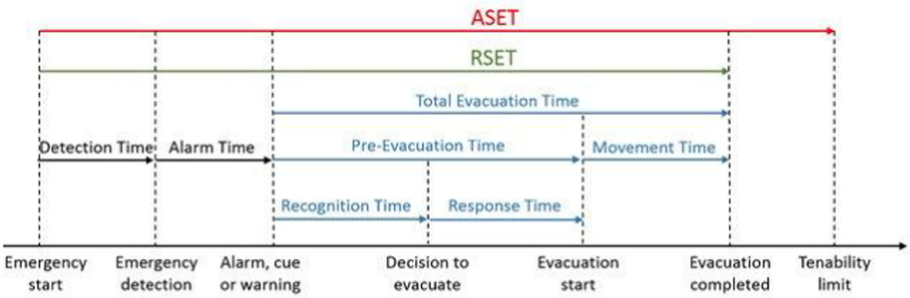


Fig. 1. The pre-movement time component of the evacuation timeline concept. *Cited from* Zhao et al. (2020) [33].

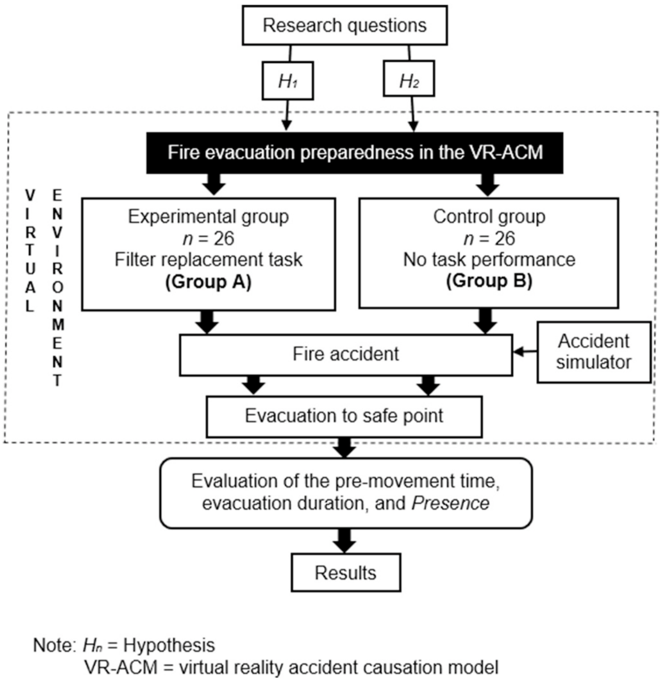


Fig. 2. The conceptual experiment model.

- The maximum exposure to carbon monoxide (CO) concentration was at 1200 parts per million (ppm) of air, the average for 5 min according to the British standard published document (BS PD) 7974–6:2019 [34], which prohibits worker exposure to any CO level above this limit.
- The air temperature tenable limit was not to exceed 60 °C according to the BS PD 7974–6:2019 guideline for the temperature limit that can endanger human life [34].

These criteria were factored as a time component by the accident simulator for occupants to egress before the fire effluents exceeded the limits for sustaining human life. During the fire, the simulator displayed these invisible quantities as smoke [35]. Primarily because most lethal gases such as toxic fumes and flammable gases do not possess optical properties. For this reason, they are represented with the smoke visualization technique to make it visible to participants by real-time data conversion as smoke. With the smoke traveling speed set at 1.0 [m/s] [21] and the progression speed of fire at 0.1 [m/s], the movement represented an actual fire hazard during the impending disaster. The experiment deliberately omitted gas alarms, fire sprinklers, and automatic sirens. The intention was to allow the occupants of the powerhouse in the simulation, who were participants of this study, to identify the hazard themselves and react accordingly by initiating evacuation.

The independent variable was the experimental intervention employing the filter replacement task by group A before the fire broke out. For group A, the accident simulator was designed to trigger while installing the new filter. According to the emergency evacuation plan, and in line with fire safety engineering principles [34], all participants were informed to evacuate the powerhouse through the closest exit the moment they saw the fire. Unknown to the participants, the fire simulator triggers the fire after 8 min into the immersion. The experimental, (group A) was engaged in the maintenance work while the control, (group B) was not tasked with any responsibility before the fire outbreak. Subsequently, we measured the pre-movement duration individually from the onset of the fire until the movement began towards the exit. Following this, we compared the pre-movement time of both groups to establish whether the task had any adverse effect on group A's recognition and response compared with group B to answer RQ1.

Furthermore, we compared the total evacuation duration between the groups from when the fire began until the occupant evacuated the building to the safe point. This comparison determined whether any differences noted at the pre-movement stage were transferred to the total evacuation duration. The final measurement was the perception of the levels of *Presence* experienced in the VR by both groups to answer RQ2, which was conducted with the WS *Presence* questionnaire. Furthermore, two hypotheses *H1* & *H2* were formulated to address RQ1 and RQ2, respectively. Fig. 2 displays these procedures based on the VR-ACM model.

3.1.1. Experiment location and instruments

The experiment was conducted at the Technobothnia virtual reality research center in Vaasa, Finland, between February 2019 and October 2020. This laboratory is equipped with state-of-the-art VR gadgets and computing power suitable for the current immersive assessment. The VR play area for participants' movement in the laboratory measures 3 m by 2.2 m. An HTC Vive VR head-mounted display (HMD) (China) with a 3D earpiece provided the display and audio for the virtual environment. Additionally, there were two hand-held controllers to offer interaction and intuitive response. Likewise, two sensors were positioned at two vertices of the laboratory to track movement through the headset and touch controllers while feeding the computer as occupants of the virtual powerhouse simulation. The powerhouse and fire effluents simulation was powered by a Windows 10 desktop computer (ASUS, Taiwan) with an intel core i7 dual-core processor running at 3.6 GHz. An NVIDIA GeForce GTX 1070 graphics card having a RAM of 32 GB enhanced the 3D simulations for the HMD. The model was built with the Fusion 360 version 2.0.9305 and the Unreal real-time game engine version 4.2, designing software for creating the simulations. Additionally, we monitored the actions of each participant who acted as an occupant in the powerhouse with the aid of a 64-inch flat-screen monitor (Fig. 3b).

3.1.2. Participants' selection

We recruited participants by emails and personal contacts in four universities in Vaasa, Finland. The inclusion criteria comprised university students with a minimum age of 20 years and without cognitive or motor limitations and normal or corrected-to-normal vision. A total of 52 participants, consisting of 11 (21.15%) women and 41 (78.85%) men with a mean age of 24.8 ± 6.1 years, were recruited for the experiment. This number of participants is per Gall et al.'s (1996) recommendation for the requirement of a minimum

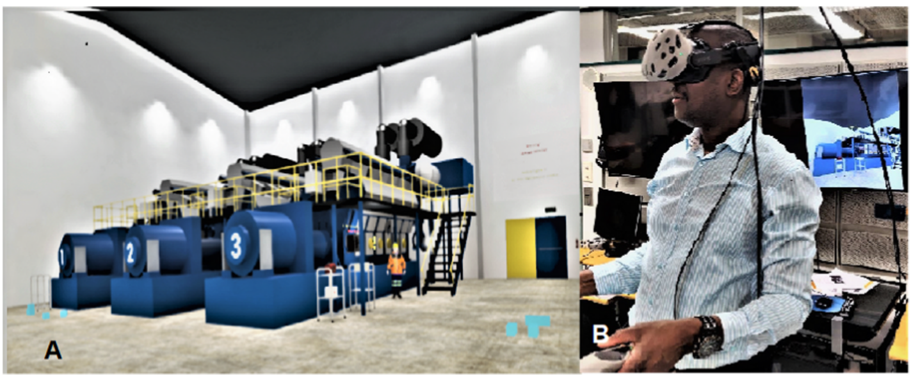


Fig. 3. a. The powerhouse with the three engines. b. Immersion into the powerhouse simulation.

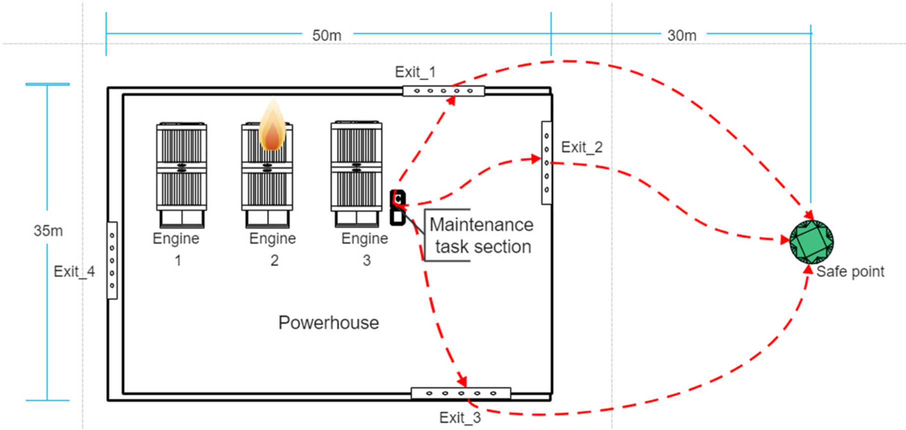


Fig. 4. The plan elevation of the powerhouse.

of 15 participants for an experiment, which Cohen et al. (2007:102) reiterate as the minimum number appropriate for an experimental group as well as in the control group for comparison [36,37]. Participants were randomly assigned to one of the two groups. Thence, the groupings are presumed to be fairly distributed to prevent any bias. Their educational pursuits at the time were as follows: First degree = 17 (32.7%), Master's degree = 26 (50%), and Ph.D. = 9 (17.3%). Participation was completely voluntary, and all the participants individually signed the informed consent form after receiving explanations of the experiment procedure.

3.1.3. Features of the powerhouse

The powerhouse is a conceptual rectangular single-story building design with a simple layout classified as B1 (Fig. 4) according to the BS PD 7974–6:2019 standard [11,34]. With a building space measuring 50 m long, 35 m wide, and 9.84 m high, the facility mainly contained three 16 MW gas-powered engines (Fig. 3a) that run on liquefied petroleum gas (LPG) and natural gas. An optimum lighting intensity of 400 lux was ensured in the vicinity according to the *American National Standard Practice for Industrial Lighting* (ANSI:1991) [38] for large-scale visual tasks. Having an exit on each of the four sides of the building with conspicuous signs that leads directly to the open space, the building design satisfies the exit requirements of the confederation of fire protection associations in Europe (CFPA E) [39]. This guideline is for fire safety engineering designs for evacuating safely from a building during emergencies [39].

3.2. Experiment procedure

Immersion into the powerhouse began when the participants individually wore the HMD headset and, with the controllers in hand, waited for the visual display of the interior of the powerhouse and gas-fired engines (Fig. 3b). The simulation presented every movement of the immersed person's head and hands in real-time according to a participant's line of sight and actions via the controllers. Interaction and control of equipment and machinery in the powerhouse occurred through this means. Navigation, controlling equipment, and walking in the simulation were possible by activating the controllers' assigned teleport and control buttons. As most of the participants lacked prior exposure to VR, we tested navigation in the simulation for a maximum of 10 min with the packing of cubes from the plant floor onto a trolley, as displayed in Fig. 5. The purpose of this initial exercise in the virtual realm was to enable both participating groups to become familiar with the VR gadgets for performing general tasks and evacuating from the powerhouse. The total exposure time in the immersion did not last more than 25 min, according to the HTC factory-recommended duration of fewer than 30 min per immersion with 10 min break if needed [40]. On average, the time for performing the entire experiment, including data collection from the questionnaire, lasted approximately 45 min for each participant of both groups.

3.3. The engaging air filter replacement task

Fig. 4 also demonstrates the location of the 3rd engine where the filter replacement task occurred. As aforementioned, the control group was not tasked with any responsibility, and they could freely explore and scrutinize the features of the powerhouse. Both groups were informed to evacuate through the closest exit (Fig. 4) to the safe point immediately after seeing the fire as previously directed in the emergency evacuation plan. Five phases (PH1 – PH5) were outlined for group A and four phases (PH1, PH2, PH4, and PH5) for group B, and these are explained as:

PH1: Familiarization of the features of the HMD and controllers for navigation and interaction in the simulation while immersed.

- Survey the plant to identify all exits and possible hazards.
- Move around the powerhouse and pack cubes from the floor onto a trolley in the plant. Fig. 5.

PH2: Adherence to the following emergency procedure regarding the evacuation:

- Stop all activities when a hazard is detected and move to the closest exit.
- Slide the door to open and evacuate.

Fig. 5. A participant parks cubes from the floor onto a trolley.

- Walk to the designated safe point outside the powerhouse (Fig. 4).

PH3: The preventive maintenance procedure for the air filter replacement task.

Each participant in group A received the explanation to the following procedure, which was also visually relayed to them sequentially as they performed each task in the simulation.

- Ensure that the engine is turned off.
- Push the trolley with the new filter close to the third engine, numbered 3
- Remove the filter cover and place it on the middle shelf of the trolley.
- Remove the old filter and place it on the lower shelf of the trolley.
- Pick up the new filter from the trolley and fix it in the air filter compartment of the engine.
- Pick up the filter compartment cover from the middle of the trolley and place it back to the engine.

Note: All the participants in group A were expected to identify the fire and initiate evacuation before completing this phase. As explained earlier, the accident simulator starts after 8 min into the task, and the premovement time and the time when each participant arrived at the safe point were measured in the simulation.

- PH4: Participants finally fill out the *Presence* questionnaire after the experiment.

3.4. Effects of a filter replacement task on the pre-movement time

In line with the perception that participants working on the task, group A, will not recognize the hazard early enough to initiate prompt evacuation as the control group B in the simulation, RQ1 was addressed related to this effect with the pre-movement time. Any significant differences between the mean results of the two groups answer RQ1. The first hypothesis therefore states:

- *H1:* An engaging maintenance task in a powerhouse simulation before a virtual fire outbreak adversely affects the pre-movement time in VR.

3.5. Analysis of the pre-movement time (H1)

To test *H1*, we analyzed the differences in the pre-movement time of the two groups by running the independent sample *t*-test between the mean of the associated populations. This was to evaluate whether a statistically significant difference existed between the results of both groups, as RQ1 sought to uncover.

3.5.1. Premovement time

In factories, warehouses, and plants, where the occupants are considered alert, awake, and aware of the workplace, the standard pre-movement time at the onset of fire is usually within 30–60 s [11,41]. This is consistent with the BS PD 7974–6:2019 standard, suggesting this duration for the first occupant within a scenario categorized “A”: *Awake and familiar* to the building [34]. Our VR-ACM eliminates alarms and expects the detection of the fire by the sight of smoke or fire. Therefore, we evaluated the recognition and response time that represent the pre-movement time of each participant from the time of the ignition of fire till movement towards the exit begun in the VR.

3.6. Effects of the filter replacement task on the level of presence

Both groups answered the WS questionnaire for assessing the *Presence* level experienced in the immersive environment (RQ2). The objective was to establish if a significant effect was evident on any of the five factors of the *Presence* questionnaire as afore explained. We thus posit *H2*.

- *H2:* An engaging maintenance task ahead of an emergency virtual fire evacuation in VR increases the experience of *Presence* in the simulation.

4. Results

This section presents the results of this study, which aimed to evaluate the effects of an engaging air filter replacement task on the pre-movement time during a fire accident that required early recognition towards evacuation. These results answer our RQs as stated in *H1 and H2.* To do this, we run the independent sample *t*-test in SPSS *v*26 to determine if a difference exists between the mean of the results of the two groups. However, we first analyzed the sample characteristics for normality.

4.1. Sample characteristics

According to Shapiro & Wilk (1965), the *t*-test parametric statistical method for evaluating the differences between the means of two groups requires that the dependent variables are approximately normally distributed for each category of the independent variables [42]. Thus, we first evaluated these by the z-values of the Skewness and Kurtosis scores for each group, tested to be between (−1.96 and + 1.96) [42] standard deviations for normal distribution in Table 1. Secondly, the data for both groups were skewed and kurtotic according to the eyeball test of the histogram (Appendix A and B) and the Q-Q plots (Appendix C and D). However, they do not differ significantly from normality as all the four z-values (Table 1) were within the specified range. Therefore, this holds the assumption that our data were approximately normally distributed [43].

4.2. The effect of the filter replacement task on the evacuation time

Table 2 presents the averages of the pre-movement time and the evacuation durations for both groups, the standard deviation, and the *p*-value to test if these differences are extreme. A mean pre-movement time of 60.12 s was recorded for the experimental (group A) while the control (group B) recorded 39.58 s which amounts to a 20.84-s difference between the two groups before initiating evacuation. Furthermore, the independent sample *t*-test was run to determine if this difference between the mean of the groups was statistically significant. The obtained value in the table was $t = 3.26$ and a *p*-value of .002 at a significant level of $p = .05$. Having a degree of freedom (*df*) at 25 for each group, the effect size, according to Cohen's *d* was measured at 0.905. Similarly, the table presents the mean evacuation duration of the control group, which resulted in 64.58 s, while that of the experimental group trailed behind at 82.42 s.

4.3. Presence and interactivity levels

This section presents the results of RQ2, which sought to investigate how the emergency evacuation during the maintenance task affected participants' perception of *Presence* in the VR environment as *H2* postulates. Table 3 presents these results according to the WS *Presence* questionnaire for groups A and group B. Accordingly, this table displays the mean, standard deviation, p-value, and t-values for the factors most affected by the maintenance task in the simulation.

Table 1
Distribution of variables.

Participants	Description	Statistics	Std. Error	z-values
Experimental group	Skewness	.896	.456	1.96
	Kurtosis	.376	.887	.42
Control group	Skewness	.584	.456	1.28
	Kurtosis	-.782	.887	.882

Table 2
Statistical differences in the pre-movement time and the total evacuation duration between the experimental (group A) and control (group B).

Groups	A ($n = 26$)		B ($n = 26$)		Δ (Sec)	Cohen's *d*	*t*	*df*	*p*
	M	*SD*	*M*	*SD*					
Pre-movement time	60.12	23.94	39.58	21.39	20.54	0.905	3.26	50	.002
Evacuation duration	82.42	18.01	64.58	18.34	17.84	0.982	3.54	50	.001

Table 3
Results of the *Presence* level of experimental (group A) and control (group B) in VR.

Factor	Group A		Group B		α = .05	*t*	*df*	95% CI
	M	SD	M	SD				
Sensory	5.92	0.43	5.79	0.42	P = .29	1.07	50	[-0.141, 0.306]
Realism	6.06	0.65	5.85	0.68	P = .26	1.15	50	[-0.158, 0.581]
Involvement	5.94	0.47	5.59	0.61	P = .03	2.30	50	[-0.044, 0.166]
Control	5.83	0.32	5.70	0.47	P = .25	1.17	50	[-0.093, 0.352]
Distraction	6.06	0.44	5.79	0.46	P = .04	2.16	50	[0.019, 0.519]

5. Discussions

This chapter explains the pre-movement time and the total evacuation duration results while participants were engaged in the task when the fire erupted in a VR simulation. Analysis of the *Presence* and *interactivity* levels experienced in the VR also follows. These results answer our RQs according to the experimental task (group A) and the control (group B). As explained earlier, the participants in group A performed the air filter task replacement by following visual instructions on a gas-powered engine. However, group B (control) was not engaged in any maintenance tasks in the simulation when the fire broke out. Both groups evacuated the powerhouse as soon as they detected the virtual fire triggered by an accident simulator. The simulator displayed the fire dynamics with the fire effluent as smoke for both groups of the experiment who acted as occupants of the powerhouse to initiate the necessary evacuation response.

5.1. The effect of the engaging maintenance task on the pre-movement time and evacuation duration

Referring to Table 2 at the results section, which addresses *H1* while answering RQ1, the mean pre-movement time of (M = 60.12, SD = 23.94) for the experimental group compared to that of the control group (M = 39.58, SD = 21.39) amounted to 51.89% difference, which is a substantial delay for the pre-movement time during a fire evacuation. From the independent sample t (50) = 3.26, and p = .002, which is less than 0.05, suggests that the intervention was statistically significant according to Cox (1966) [43]. Similarly, the effect size of 0.905 according to Cohen's d implies that this effect was substantial and supports our assertion in *H1*. For this reason, we can confidently affirm *H1*; that replacing the air filter in VR caused a substantial delay in the pre-movement time. Consequently, the experimental participants did not see the fire to evacuate as early as the control group. As participants were explicitly informed in the emergency evacuation plan (PH2 of section 3.3) before the experiment to stop working and evacuate the moment they saw a hazard, the noted delay was, therefore, largely a result of the lack of awareness due to the decline in the perception of other occurrences in the plant. On the other hand, the obtained mean evacuation duration results of the two groups (group A = 64.58 s) and group B (82.42 s) equally had a statistically significant difference measured at (t-test = 3.54, and p = .001). These differences also suggest a transfer of the pre-movement delay to the evacuation delay of the experimental group.

Besides, similar fire evacuation research findings in VR support these findings. For example, Cao et al. (2019) way-finding simulation while tasked with treasure hunting in a museum [15] and the experiment by Bourhim and Cherkaoui (2020) on pre-evacuation behavior during an emergency fire in VR, who compared their results with data from actual fire conditions [5]. Notwithstanding, it is necessary to compare the present study results to an actual powerhouse emergency fire drill consisting of a maintenance task with a similar work environment. Furthermore, due to the causes of some evacuation delays in real life, such as evacuees collecting personal items and making phone calls before initiating evacuation, as Bourhim and Cherkaoui (2020) explain [5], such a comparative study would be necessary to validate the experiment ecologically.

5.2. Presence and interactivity level analysis

According to the results presented in Table 3 in answer to RQ2, which sought to address the effects of the emergency evacuation during the maintenance tasks on participants' perception of *Presence* in the VR environment, the five factors of the *Presence* questionnaire produced mixed results. With the *control factor*, both the filter replacement task group and control group indicated high levels according to the 7-point scale (M = 5.83 SD = 0.32) and (M = 5.70, SD = 0.47) respectively. These values suggest that most participants experienced an appreciable level in controlling objects and machinery in the VR environment. Similarly, the values obtained for the *sensory factor* on the same scale for the task (M = 5.92, SD 0.43) and the control (M = 5.79, SD = 0.42) imply that both groups moved freely and thus perceived the VR environment and context to be rich and interactive. The *realism factor,* which represents how participants perceived the simulation to be real and meaningful, produced similar results (M = 6.06, SD = 0.65) and (M = 5.85, SD = 0.68) for the air filter experimental group and the control group, respectively. However, both the *involvement factor* and the *distraction factor* yielded significantly different results for the two groups. Particularly, these two factors represent how participants felt their *Presence* while immersed in the simulation and how close to reality they experienced the interaction within the virtual environment. In the *involvement factor*, whereas the experimental group scored (M = 5.94, SD = 0.47), the control group's score dropped convincingly (M = 5.59, SD = 0.61). Accordingly, these differences t (50) = 2.30, p = .03 are significant in line with the t-test at 95% confidence interval. Likewise, the results of the *distraction factor* (M = 6.06, SD = 0.44) for the experimental group and (M = 5.79, SD = 0.46) for the control group signals that the differences between the two groups t (50) = 2.16, p = .04 is also significant at 95% confidence interval. These variations are because, apart from the initial task of picking boxes from the floor and placing them on the trolley, and opening the door for evacuation as both groups experienced, the visual instructions coupled to the process of replacing the air filter caused a further engagement in the simulation. This is believed to result in the noted increase in the experimental groups' sense of *Presence*. Removing the filter cover and placing it on the trolley, picking the new filter from the trolley, and fixing it at the correct location on the engine before covering tended to reinforce a further sense of *interactivity* and *control* for the experimental group.

Consequently, this bolstered their sense of *involvement* and *distraction* according to the *Presence* measurement. We can thus conclude as *H2* postulates that the maintenance task in VR contributed to a higher level of *Presence*. The construct reliability of the *Presence* results was also satisfactory since the combined constructs exhibited a Cronbach's alpha of 0.716.

5.3. Contributions and implications

The current study's findings add to VR interactive fire safety drill research by demonstrating that participants can experience real-time emergency fire situations that necessitate evacuations in a controlled and safe virtual simulation environment. Besides, the immersive environment can be suitable for assessing the pre-movement time, which is vital for safe evacuation from a building.

- Generally, the study manifests the importance of exercising adequate levels of safety awareness while executing engaging tasks, especially in high-risk occupational settings such as in a gas-powered house.
- Specifically, the study demonstrates that captivating practices in a powerhouse simulation, such as engagement in a maintenance task, need to be undertaken with awareness of other occurrences like smoke in the vicinity that can endanger one's safety.
- The pre-movement time is an essential component during fire evacuations in VR since a delay at this stage is transferable to the entire evacuation delay, which is crucial during fire evacuations.
- Performing an engaging maintenance task in VR increases the *involvement and distraction* factors that represent the degree of *interactivity* and the sense of adaptation of participants according to the *presence* measurement, which is an essential ingredient for evaluating the degree of reality in a VR simulation.
- Although the evacuation speed in the immersive simulation may be synthetic, which is a general limitation of VR simulations [5], the study however holds immense significance at the pre-movement phase to which the merits of fire safety evacuations are exploited to further broaden VR utilization for realistic safety assessments. Other studies, for example, Cha et al. (2012) [35], Bhide, S. (2017) [4], Feng et al. (2018), and Kwegyir-Afful et al. (2021) [2], also performed similar fire evacuation simulations in VR, which validates the findings of the current study within VR research.

5.4. Limitations and future works

Despite this experiment's underlined contributions and benefits, the study encountered some limitations and constraints necessary for discussion, which also serves as the basis for further research in this direction. Firstly, the simulation did not consider a crowded fire accident evacuation situation that usually results in many casualties. This is mainly because our immersive VR setup could handle only one user at a time. Secondly, according to Ref. [22]Kinateder et al. (2014), social influence has been shown to affect evacuation decisions in VR [22]. Therefore, we hope to incorporate multiple users in the future for fire emergency drills simultaneously. Secondly, our setup consisted of only haptic feedback with audio-visual sensations for interactions in the simulation. In the future, we could incorporate a multisensory interface such as olfactory and thermal sensations to increase the level of *realism* in the virtual realm, as demonstrated by Shaw et al. (2019) [7].

Furthermore, the *Presence* measurement of the immersive encounter was recorded after the experiment, as the usual practice. However, the limitation of such post-immersive questionnaires is that they are subject to participants' memories. Since memories are also subject to individual retention capabilities, the consistency of the results can be affected. In the future, we hope to include questionnaires for answering while participants are immersed in the simulation. After the experiment, we also hope to conduct interviews to understand why some participants generally delay evacuating while engaged with similar maintenance tasks. Future interviews after the task-based evacuation could also ask whether participants wanted to complete the task before initiating evacuation. Lastly, this research also shares the same ecological validity issue, which all VR fire investigations, assessments, and training encounter due to the differences between actual fire situations and virtual simulations [5].

6. Conclusions

The study investigated the effect of an air filter replacement task on participants' responses during a virtual fire emergency that necessitated evacuation from a powerhouse simulation. Several records of the pre-movement duration and individual perceptions of the evacuation drill in the simulation environment were obtained as feedback from the participants who were immersed as occupants of the powerhouse. These participants were divided into two groups: the experimental (group A) and the control (group B). The experimental group was tasked to replace the air filters on a gas-powered engine during the fire eruption. The control group, however, was not assigned any responsibility during the fire. Both groups were to evacuate the powerhouse as soon as they recognized the hazard. The analysis of the mean pre-movement time for both groups realized that the experimental group significantly delayed recognizing the fire to initiate an early evacuation. Consequently, the results indicate a transfer of this delay to the evacuation duration of the experimental group. Moreover, the experimental group perceived the simulation environment to be more natural and interactive than the control, suggesting that the task added a higher sense of engagement that increased their level of *Presence*. The significant findings according to the hypotheses were highlighted as:

(a) An air filter replacement task in VR can affect the pre-movement time by causing substantial delays, which transcend further to minimize the evacuation duration in the VR simulation.

(b) Results of the *Presence* measurement generally imply that both participating groups experienced a high level of *realism* with the extra feeling of *interactivity* by the experimental group due to the maintenance task in the VR simulation.

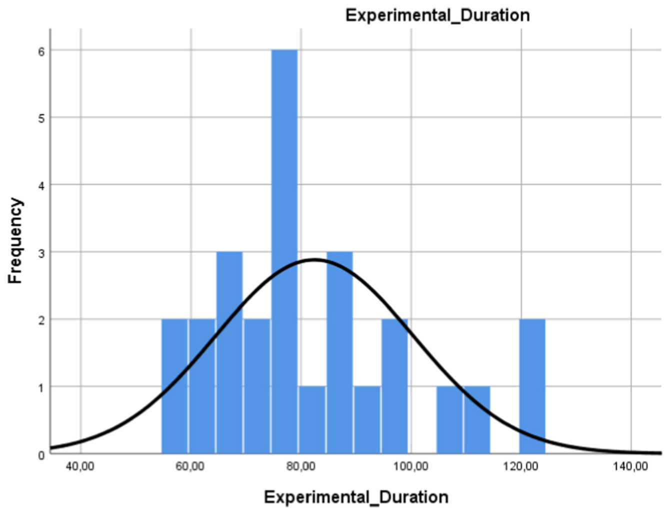
Declaration of competing interest

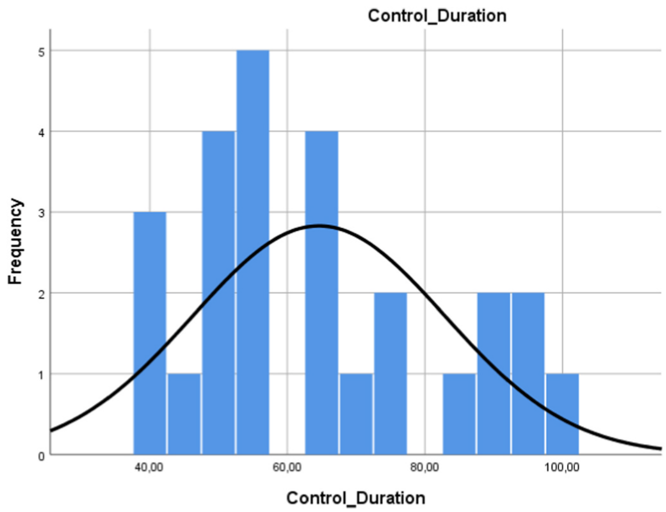
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

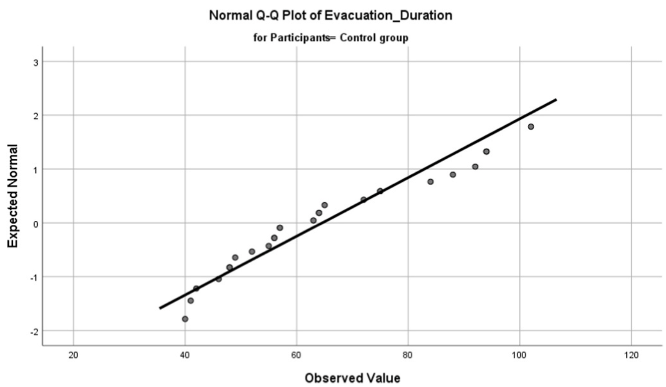
Acknowledgments

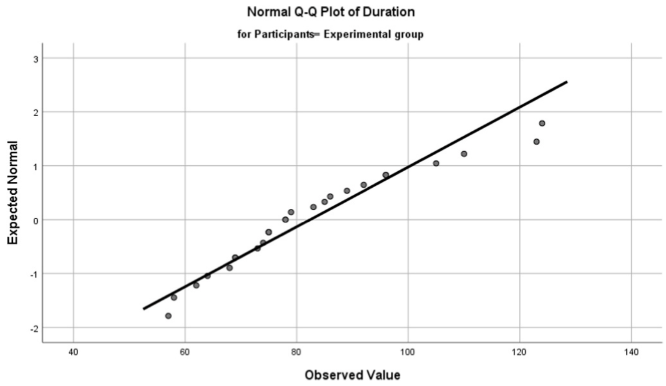
The author of this article wishes to express his profound appreciation and thanks to the staff at the Virtual Reality Laboratory at the Technobothnia Research Center. Vaasa, Finland.

Appendices.


Experimental_Duration
Frequency
0
1
2
3
4
5
6
40,00
60,00
80,00
100,00
120,00
140,00
Experimental_Duration


Control_Duration
Frequency
0
1
2
3
4
5
40,00
60,00
80,00
100,00
Control_Duration


Normal Q-Q Plot of Evacuation_Duration
for Participants= Control group
Expected Normal
-2
-1
0
1
2
3
20
40
60
80
100
120
Observed Value



References

[1] W. Qi-quan, Y. Xiang-dou, Risk analysis and control measure of gas power generation enterprise, Int. J. Sci. Qual. Anal. 3 (2017) 15.
[2] E. Kwegyir-Afful, T.O. Hassan, J. Kantola, Simulation-based assessments of fire emergency preparedness and response in virtual reality, Int. J. Occup. Saf. Ergon. (2021) 1–30.
[3] Z. Feng, V.A. González, R. Amor, R. Lovreglio, G. Cabrera-Guerrero, Immersive virtual reality serious games for evacuation training and research: a systematic literature review, Comput. Educ. 127 (2018) 252–266.
[4] S. Bhide, Fire Safety and Emergency Evacuation Training for Occupants of Building Using 3D Virtual Simulation, 2017.
[5] E.M. Bourhim, A. Cherkaoui, Efficacy of virtual reality for studying people's pre-evacuation behavior under fire, Int. J. Hum. Comput. Stud. 142 (2020) 102484.
[6] P.S. Nimlyat, A.U. Audu, E.O. Ola-Adisa, D. Gwatau, An evaluation of fire safety measures in high-rise buildings in Nigeria, Sustain. Cities Soc. 35 (2017) 774–785.
[7] E. Shaw, T. Roper, T. Nilsson, G. Lawson, S.V. Cobb, D. Miller, The Heat Is on: Exploring User Behaviour in a Multisensory Virtual Environment for Fire Evacuation, 2019, pp. 1–13.
[8] S. Gwynne, E. Galea, J. Parke, J. Hickson, The collection and analysis of pre-evacuation times derived from evacuation trials and their application to evacuation modelling, Fire Technol. 39 (2003) 173–195.
[9] M. Manes, D. Rush, Assessing fire frequency and structural fire behaviour of England statistics according to BS PD 7974-7, Fire Saf. J. (2020) 103030.
[10] K. Dhalmahapatra, S. Das, J. Maiti, On accident causation models, safety training and virtual reality, Int. J. Occup. Saf. Ergon. (2020) 1–32.
[11] J. Pauluhn, Estimation of time to compromised tenability in fires: is it time to change paradigms? Regul. Toxicol. Pharmacol. 111 (2020) 104582.
[12] S. Aromaa, K. Väänänen, Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design, Appl. Ergon. 56 (2016) 11–18.
[13] T. Fujimi, K. Fujimura, Testing public interventions for flash flood evacuation through environmental and social cues: the merit of virtual reality experiments, Int. J. Disaster Risk Reduct. 50 (2020) 101690.
[14] H. Markwart, J. Vitera, S. Lemanski, D. Kietzmann, M. Brasch, S. Schmidt, Warning messages to modify safety behavior during crisis situations: a virtual reality study, Int. J. Disaster Risk Reduct. 38 (2019) 101235.
[15] L. Cao, J. Lin, N. Li, A virtual reality based study of indoor fire evacuation after active or passive spatial exploration, Comput. Hum. Behav. 90 (2019) 37–45.
[16] Y. Zhou, Y. Pang, F. Chen, Y. Zhang, Three-dimensional indoor fire evacuation routing, ISPRS Int. J. Geo-Inf. 9 (2020) 558.
[17] D. Wang, Y. Yang, T. Zhou, F. Yang, An investigation of fire evacuation performance in irregular underground commercial building affected by multiple parameters, J. Build. Eng. 37 (2021) 102146.
[18] M. Zhang, J. Ke, L. Tong, X. Luo, Investigating the influence of route turning angle on compliance behaviors and evacuation performance in a virtual-reality-based experiment, Adv. Eng. Inf. 48 (2021) 101259.
[19] V. Schwind, P. Knierim, N. Haas, N. Henze, Using Presence Questionnaires in Virtual Reality, 2019, pp. 1–12.
[20] H. Zou, N. Li, L. Cao, Emotional response–based approach for assessing the sense of presence of subjects in virtual building evacuation studies, J. Comput. Civ. Eng. 31 (2017) 04017028.
[21] J. Kritikos, C. Zoitaki, G. Tzannetos, A. Mehmeti, M. Douloudi, G. Nikolaou, G. Alevizopoulos, D. Koutsouris, Comparison between full body motion recognition camera interaction and hand controllers interaction used in virtual reality exposure therapy for acrophobia, Sensors 20 (2020) 1244.
[22] M. Kinateder, E. Ronchi, D. Nilsson, M. Kobes, M. Müller, P. Pauli, A. Mühlberger, Virtual Reality for Fire Evacuation Research, 2014, pp. 313–321.
[23] C. Tang, W. Wu, C. Lin, Using virtual reality to determine how emergency signs facilitate way-finding, Appl. Ergon. 40 (2009) 722–730.
[24] B.G. Witmer, M.J. Singer, Measuring presence in virtual environments: a presence questionnaire, Presence 7 (1998) 225–240.
[25] B.G. Witmer, C.J. Jerome, M.J. Singer, The factor structure of the presence questionnaire, Presence, Teleoperators Virtual Environ. 14 (2005) 298–312.
[26] F. Global, Property Loss Prevention Data Sheets, 2016, 2-1.
[27] B. Sarwar, I.S. Bajwa, S. Ramzan, B. Ramzan, M. Kausar, Design and application of fuzzy logic based fire monitoring and warning systems for smart buildings, Symmetry-Basel. 10 (2018) 615.
[28] A. Sadeghi, M. Jabbari, M. Rezaeian, A. Alidoosti, D. Eskandari, Fire and explosion risk assessment in a combined cycle power plant, Iran, J.Chem.Chem.Eng.Research Article 39 (2020).
[29] P.R. Amyotte, S. Berger, D.W. Edwards, J.P. Gupta, D.C. Hendershot, F.I. Khan, M.S. Mannan, R.J. Willey, Why major accidents are still occurring, Curr. Opin. Chem. Eng. 14 (2016) 1–8.
[30] T. Jin, Visibility through Fire Smoke, Part 5. Allowable Smoke Density for Escape from Fire, Report of Fire Research Institute of Japan, 1976, p. 12.
[31] M. Spearpoint, C. Hopkin, A study of the time of day and room of fire origin for dwelling fires, Fire Technol. 56 (2020) 1465–1485.
[32] B. Schröder, L. Arnold, A. Seyfried, A map representation of the ASET-RSET concept, Fire Saf. J. 115 (2020) 103154.
[33] X. Zhao, R. Lovreglio, D. Nilsson, Modelling and interpreting pre-evacuation decision-making using machine learning, Autom. ConStruct. 113 (2020) 103140.
[34] British Standards Institution, PD 7974-6: application of fire safety engineering principles to the design of buildings, in: Human Factors. Life Safety Strategies. Occupant Evacuation, Behaviour and Condition (Sub-system 6, British Standards Institution, London, UK, 2019.
[35] M. Cha, S. Han, J. Lee, B. Choi, A virtual reality based fire training simulator integrated with fire dynamics data, Fire Saf. J. 50 (2012) 12–24.
[36] M.D. Gall, W.R. Borg, J.P. Gall, Educational Research: an Introduction, Longman Publishing, 1996.
[37] L. Cohen, L. Manion, K. Morrison, R. Morrison, Research Methods in Education, Routledge, 2007.
[38] Illuminating Engineering Society of North America, American National Standard Practice for Industrial Lighting, American National Standards Institute, 1991, ANSI/IES RP-7,6,38 (1991).
[39] Cfpa, CFPA-E Guideline No 19:2009 F (2019, 2019, 9 27.

[40] S. Casterson, Htc Vive: A Guide for Beginners, Conceptual Kings, 2016.
[41] E. Galea, M. Owen, S. Gwynne, Principles and Practice of Evacuation Modeling, second ed., 1999.
[42] S.S. Shapiro, M.B. Wilk, An analysis of variance test for normality (complete samples), Biometrika 52 (1965) 591–611.
[43] D. Cox, P. Lewis, The Statistical Analysis of, Series of Events, 1966.