



Assessment of Firefighters' Exposure and Response to a High-Intensity Virtual Reality Simulation

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He was also nominated for 2004 UNI Book and Supply Outstanding Teaching Award, March 2004, and nominated for 2006, and 2007 Russ Nielson Service Awards, UNI. Dr. Pecen is an Engineering Technology Editor of American Journal of Undergraduate Research (AJUR). He has been serving as a reviewer on the IEEE Transactions on Electronics Packaging Manufacturing since 2001. Dr. Pecen has



served on ASEE Engineering Technology Division (ETD) in Annual ASEE Conferences as a reviewer, session moderator, and co-moderator since 2002. He served as a Chair-Elect on ASEE ECC Division in 2011. He also served as a program chair on ASEE ECCD in 2010. He is also serving on advisory boards of International Sustainable World Project Olympiad (isweep.org) and International Hydrogen Energy Congress. Dr. Pecen received a certificate of appreciation from IEEE Power Electronics Society in recognition of valuable contributions to the Solar Splash as 2011 and 2012 Event Coordinator. Dr. Pecen was formerly a board member of Iowa Alliance for Wind Innovation and Novel Development (www.iawind.org/board.php) and also represented UNI at Iowa Wind Energy Association (IWEA). Dr. Pecen taught Building Operator Certificate (BOC) classes for the Midwest Energy Efficiency Alliance (MEEA) since 2007 at Iowa, Kansas, Michigan, Illinois, Minnesota, and Missouri as well as the SPEER in Texas and Oklahoma to promote energy efficiency in industrial and commercial environments.

Dr. Pecen was recognized by State of Iowa Senate on June 22, 2012 for his excellent service and contribution to state of Iowa for development of clean and renewable energy and promoting diversity and international education since 1998.

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Introduction

Firefighters are on the front lines, protecting lives and creating a level of emergency preparedness to assure our homeland is safe, secure, and resilient against different hazards. Firefighters respond to a wide range of unexpected incidents including medical calls, motor vehicle accidents, fires, technical rescues, explosions, hazardous material incidents, terrorism, mass casualty incidents, and to anything else, that involves a call to 911. It can be argued that firefighters are expected to respond to any type of emergency. Therefore, when the alarm sounds, firefighters must be trained, well prepared (mentally and physically), and equipped to mitigate and recover from whatever the emergency may be.

In recent years since the catastrophic event of 9/11 occurred, the fire service has been under a lot of intensive stress among the nature of threats and hazards that they face. Both the threats have changed and the role of the occupation to address these threats has changed. Firefighting equipment and technology have been advanced to include fully encapsulating ensemble, expensive technology for fire apparatus, enhanced communications, and new materials for extinguishment. However, firefighters are still losing their lives inside of burning buildings.

According to the International Association of Fire Fighters (IAFF), the injuries rate in the fire service is four times greater than in private industry, with almost a third of firefighting population being injured in the line of duty [1]. Due to the combined physiological and psychological demands of firefighting, firefighters must go through extensive training which typically takes place in a physical environment "classroom" with the implementation of the standard operating guidelines taking place during live - fire training scenes [2]. These scenes require tremendous efforts and assets including training personnel, specialized training facilities and carefully planned live - fire scenes, as well as new training models for each single training activity [2]. There is a claim that the fire service has failed to keep up with preparing for the variety of emergency situations [3].

The fatal incidents of firefighters in the line of duty is a complex problem and likely a combination of different factors: lack of experience, a wide variety of hazards, inadequate training, lack of opportunity for "on the job" training, and fire service culture. Moreover, the reduction of fire incidents over the years might lead to a sense of complacency that has severely inhibited preparedness. The suggested increase in the rate of firefighters who have lost their lives inside burning buildings points to the need to design and implement an enhanced training program. This program needs to be designed targeting firefighters and help motivate and prepare them for the changing nature of the job. Perhaps firefighters are prepared for the variety of problems in the field, but they do not have the capability to react at the moment and respond appropriately.

Simulation (e.g. virtual reality simulation) can provide a safe, ethical, and cost-effective alternative to practice in certain real fire scenes. This can serve in two ways: it can give a better understanding of new trainees' behavior and how can be shifted to safe behavior and offer trainees the opportunity to have effective and component training. By using simulations of virtual buildings with virtual fire environments, trainees can interact with a changing environment simulate various work-related procedures and/or judge whether a building design is

reasonable from a fire safety point of view. Virtual simulation permits professional trainers to assess new trainees' behavior in the response to emergency situations that may not easily be recreated in the real-world due to ethical, safety, cost, and time concerns.

Literature Review

There is a research gap in term of understanding about effective training solutions capable of preparing firefighters for ever-changing threats. To be more specific, the issue is the knowledge gap when considering high intense scenarios in the fire service. The academic knowledge gap is in the lack of training solutions for such incidents. Virtual reality (VR) simulations have the potential to generate significant benefits to fire service training. These solutions are a perfect match to provide much-needed experiences for high intense events, in a cost-effective and safe manner.

A research study analyzed the changing residential fire dynamics and its implications on operational timeframes [5]. The study results demonstrated the increasing hazards to firefighters in shorter time periods [5]. This shows the gap in training and experience of field commanders as many of them are unaware of changing fire dynamics.

A national requirement for firefighters upon entry into the fire service is the completion of the National Fire Protection Association's (NFPA) Firefighter classes (NFPA Standard 1001). However, firefighters do not receive additional training on fire behavior when they are promoted to officers and made responsible for decision making on the fire ground [6].

A research study conducted by a researcher from the National Institute of Occupational Safety and Health (NIOSH) identified four major causes of firefighters injuring: under-resourcing, inadequate preparation for things going wrong during operations, incomplete adoption of incident command procedures and inadequate personnel readiness [7]. Training simulations have been used in many domains, including the health professionals who needed to acquire skills, and attitudes while at the same time protecting the patients from unnecessary risks [8].

Serious games and virtual reality-based simulations (or virtual simulations) have grown as a form of teaching in many occupational settings, including firefighting [[9], [10], [11], [12]].

Current literature on the use of games and virtual reality for firefighting has primarily focused on improving team communication and incident command decision making [[9], [10], [11], [12]], but has generally ignored training with respect to physical behavior, involving firefighters in problem-solving and training exercises related to high intense situations.

Though these latter simulations and serious games were not developed with any objective related to firefighter training, the underlying software that predicts fire physical behavior in buildings forms one key element necessary in any integrated simulation for advanced fire training applications. Hence, the objective of this study was to assess firefighters' fire physical behavior, represented by physiological responses from a safe virtual reality simulation with an immersive experience. Accordingly, the first responder services instructors may need to consider revising their practices based on virtual simulation outcomes.

Methodology

A total of 7 subjects participated from students population to expose to three virtual reality (VR) environments with three levels of mental challenge activities for each environment: 1- Fighting Fire, 2- Rescue, and 3- Escape the Scene in order to investigate firefighters' physical behavior represented by the following physiological responses: heart rate, body posture, as well as the respiratory rate during VR simulation. Participants with a history of motion sickness, claustrophobia, anxiety issues, neck issues, elevated blood pressure or epilepsy were ineligible for participation.

Virtual Reality Simulations:

The virtual environment contained three burning facilities from low to high-intensity level of fire. The three-dimensional models: 1-furnished cabin (Figure 1); 2- morgue room (Figure 2a & b); and 3- survival old house (Figure 3 a, b, & c) were generated from Autodesk's Revit 2020, modified in 3D studio Max, Maya, and Cinema 4D, and are available on Unity game engine's asset store for free of charge. Unity's particle effect feature generated a localized ring of fire, and wall of fire effect with accompanying sound effects.

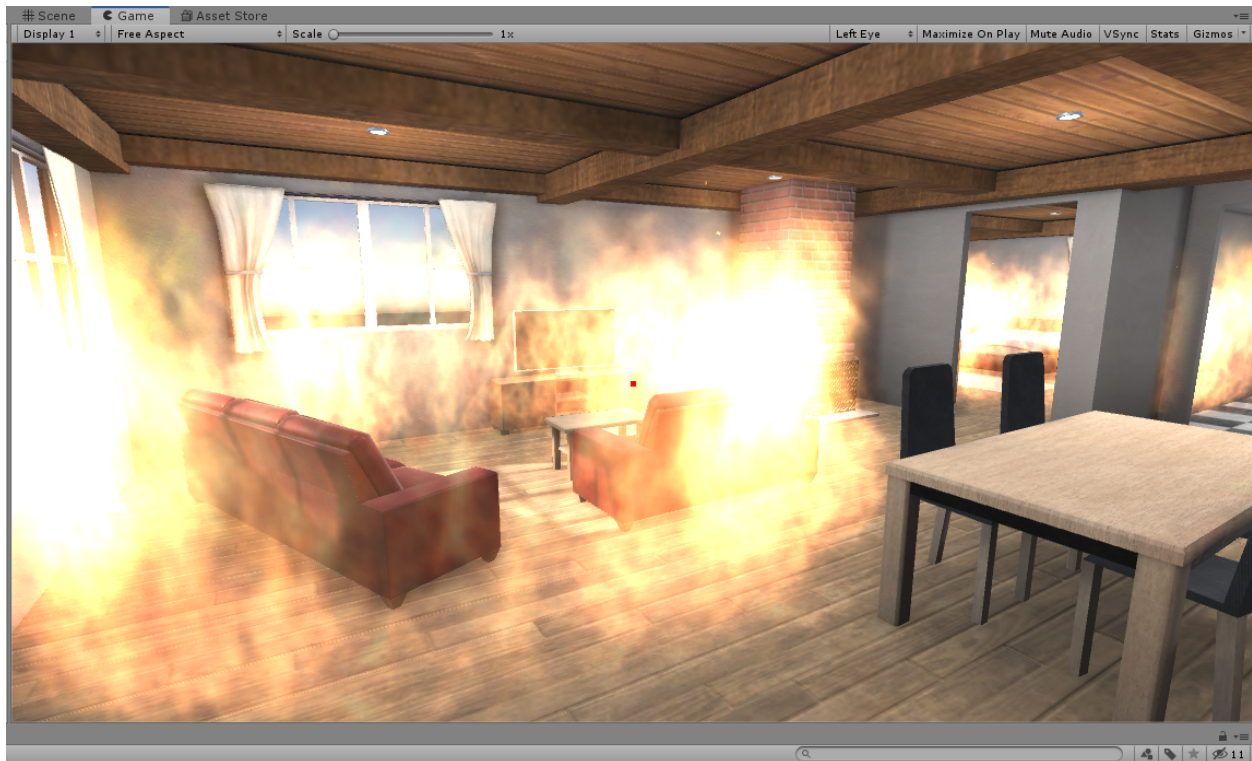


Figure 1. Furnished Cabin (Modified from J.Kaspari, Unity) virtual scene with ring of fire effect

The participants experienced immersive virtual scene on Figure 1, where the ring of fire covered the cabin. The participants' body posture, heart rate, and blood pressure were monitored as well as the motion sickness condition.

The Figure 2 a and b contain a morgue room with a wall of fire and fire explosion to provide a feeling of medium intense fire environment for the participants.



Figure 2a. Morgue room (Modified from Rockay 3D, Unity) virtual scene with wall of fire effect

Additionally, the morgue room contains slight blurriness in the scene as well as a slight sloppy control, which are to indicate that the intensity of the fire, as well as the heat inside the room, are impacting the physical condition of the first-person character. Figure 2b illustrates the fire explosion impact on the cabinets and is accompanied by the burning, melting, and fire explosion sound effects.

The researchers visited the local fire station to receive feedback and consultancy on the fire scene development to make the scenes as realistic as possible. The received feedback and suggestions were incorporated into the scenes, where the environments gradually go darker as the time progresses within the scene. The researchers initially started with a real burning room fire scene and incorporate into the VR simulation, however, the rarity of training facilities, resources, as well as the equipment's heat resistance factors steered the VR simulation to be developed in an animation and game engines. In contrast, the number of VR headsets is increasing [13] as more industries are finding a positive impact on their business activities.

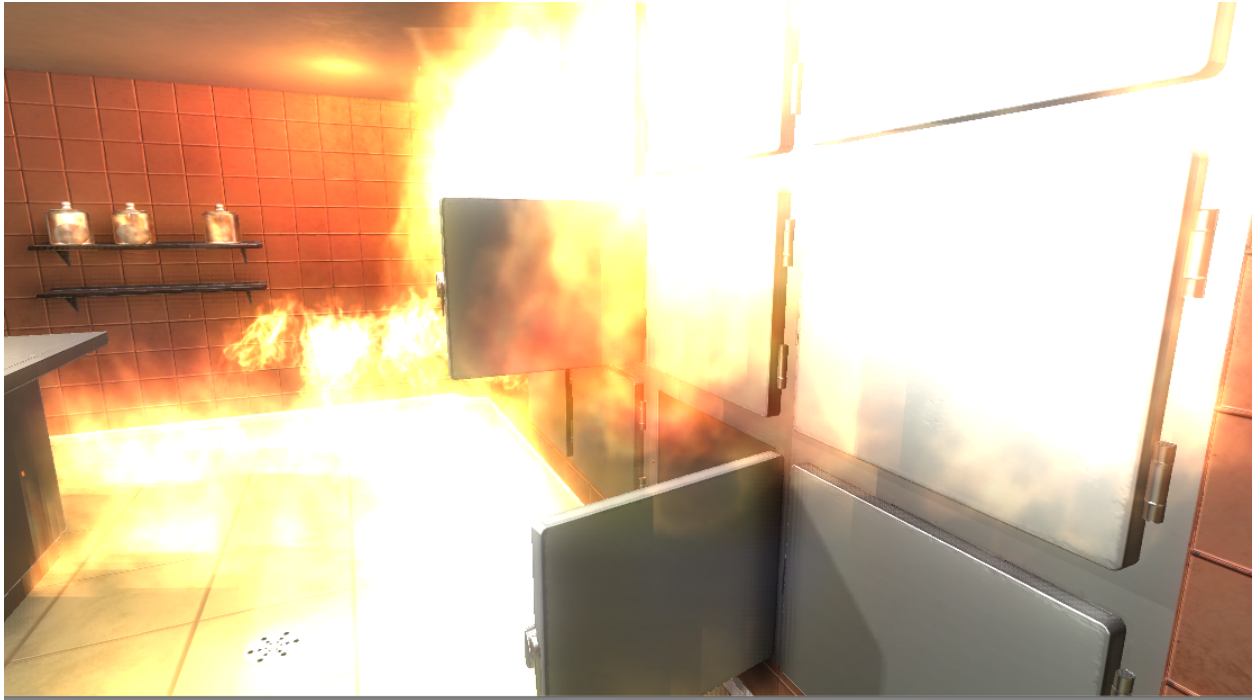


Figure 2b. Morgue room (Modified from Rockay 3D, Unity) virtual scene with wall of fire effect and explosion fire effect

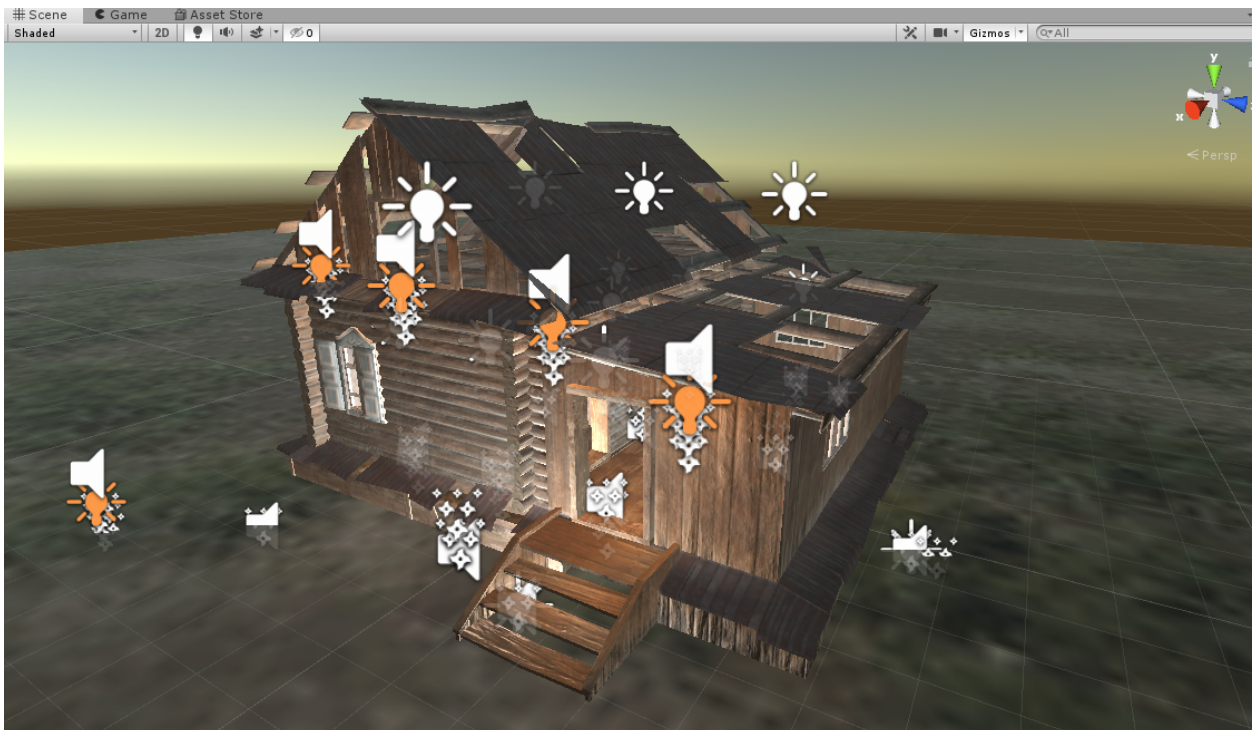


Figure 3a. Particle effect and lightning applied to the project house to imitate the dark environment



Figure 3b. Fire particle effect

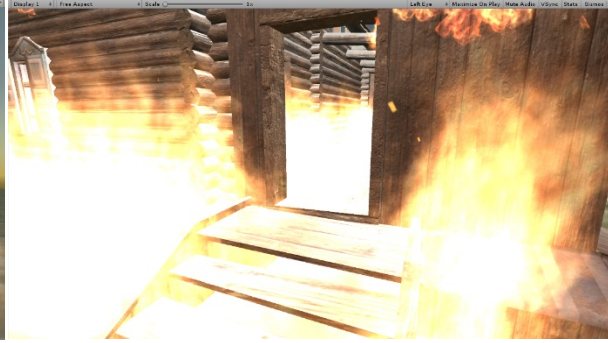


Figure 3c. Entrance and the aisles of a burning house

Total number of five students participated in the experimental virtual fire environment. The students were asked to wear the Oculus Rift S VR headset to receive immersive experience in the virtual fire scene simulation (Figures 4a & 4b). All the participants started with the Cabin scene, continued with the morgue scene, and completed with the old house scene respectively. The heart rate per scene is reported on Tables 1-5.



Figures 4a. Student participant in the morgue VR simulation



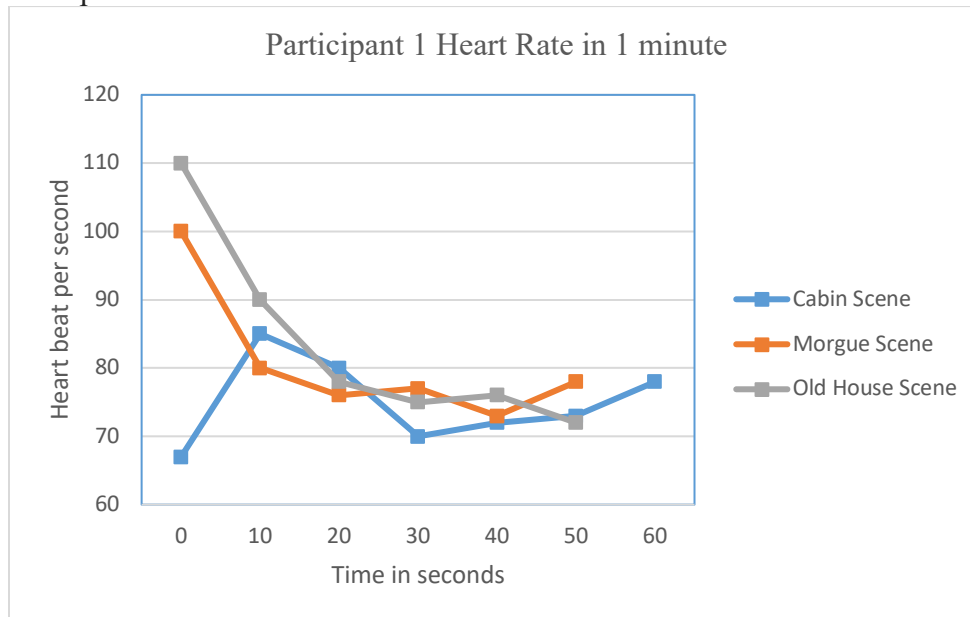
Figure 4b. Student participant experiencing Furnished Cabin VR

Physiological Monitoring: A bioharness monitor from BioHarness™ III, Zephyr Technology Corporation, Annapolis, MD was used to measure physiological responses. The Bioharness was strapped to the chest of each participant prior to starting the experimental session of virtual simulation and was worn until the end of the session.

Data Analysis

Total number of five students (age: 20.2 ± 1.4 , BMI: 25 ± 1.4) participated, from untrained firefighters population, in the fire simulating virtual reality project. The recruitment of volunteering participants' timeline was short due to the delay of ordered equipment to develop the VR environment as well as to collect the data. The first participant's heart rate started at 67 beats per minute (bpm) at 0 seconds, increased to 85 bpm at 10th - second mark up, where the participant entered the house to find the burning room (Figure 1). The participant explored the room, the heart rate stabilized at 70 bpm at 30 second mark point. A slight increase in a heartbeat (78bpm) at 60th second was observed, where the participant entered the second burning room.

Figure 1. Participant 1 Heart Rate in 60 seconds



A sudden increase in heart rate (100 bpm at 0 seconds) was observed when the student was taken to a new morgue scene (Figure 2a&b). Starting the 10th second, where the participant explored the environment, the heartbeat was stabilized throughout the whole minute. Similar to the morgue scene, the heartbeat jumped to 110bpm at 0 seconds, where the student's environment changed to the third "old house" burning scene. The reason the heartbeat on the first scene increased at 10th second rather than the 0 is due to the start of the program, where the student was taken to the welcome screen with no exposure to the fire scene.

The researchers observed similar results from participant 2 (Table 2), where the initial exposure to the virtual environment with the burning room caused excitement. Depending on the computer participants' level in computer gaming experiences, the excitement levels could have been different during the VR simulation. Table 3 shows the participant 4, whose heart rate was higher during the exploration of the morgue scene (Figure 2a&b) and peaked highest at old house burning scene (Figure 3 a, b &c).

Figure 2. Participant 2 Heart Rate in 60 seconds

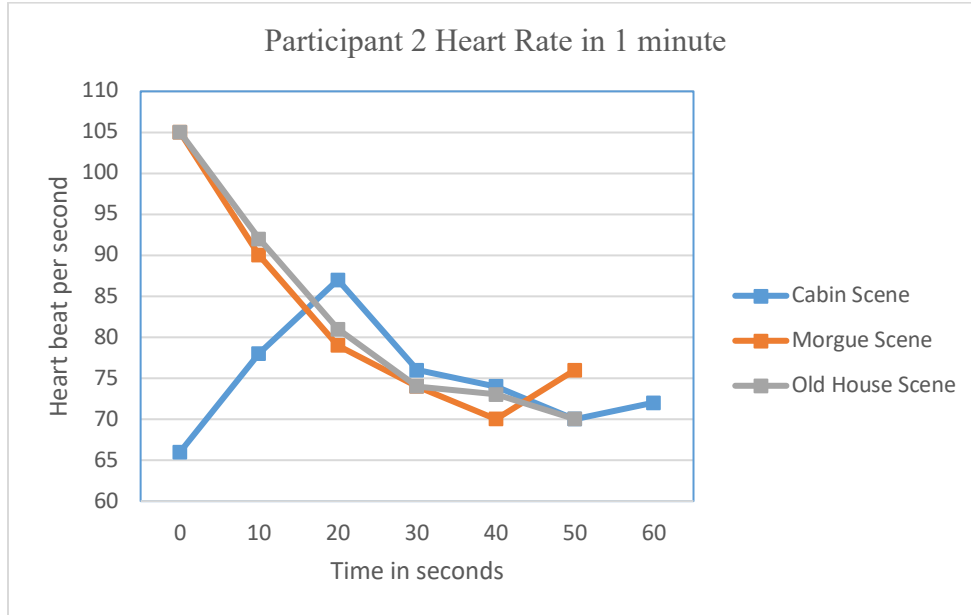
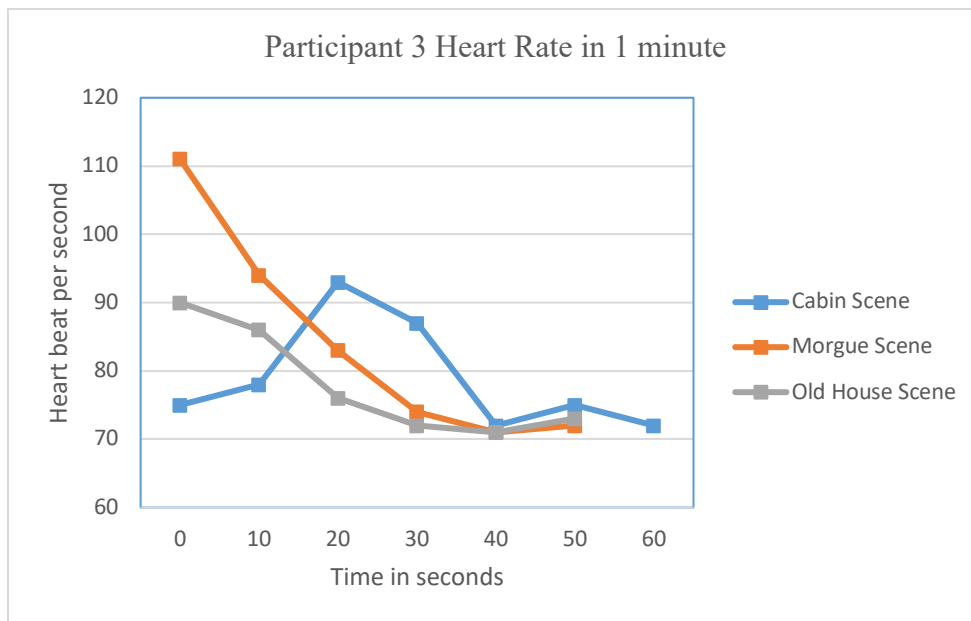


Figure 3. Participant 2 Heart Rate in 60 seconds



The researchers conducted a One-way ANOVA, in SPSS, to compare outcomes from each scene (Cabin, Morgue, and Old House) and to analyze whether there is a significant difference between the scene fire intensity levels' impact on the participants in the virtual environment. The bio harness automatically collected seven readings per participant ($5 \times 7 = 35$) for the Cabin scene and six readings per participant ($5 \times 6 = 30$) for the remaining scenes due to an error in transmitting one batch of observed data. Therefore, the researchers received total number of 95 readings from the 5 participants. The descriptive statistics shows (Table 4) that the means were relatively similar

for Morgue =82.867 and Old House=82.267, where the Old House scoring 0.6 lower average than the Morgue scene, and both greater than the Cabin mean value of 76.371

Table 4. Descriptive Statistics outcome for three intensity level fire scenes in VR

Descriptives								
Observations								
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Cabin	35.000	76.371	6.562	1.109	74.117	78.626	66.000	93.000
Morgue	30.000	82.867	11.907	2.174	78.421	87.313	70.000	111.000
Old House	30.000	82.267	12.539	2.289	77.584	86.949	70.000	110.000
Total	95.000	80.284	10.812	1.109	78.082	82.487	66.000	111.000

One-way ANOVA (Table 5) shows that there is a significant difference between the fire scenes at $p=0.024 < 0.05 = \alpha$ level from 95 total observations.

Table 5. One-way ANOVA report for three intensity level fire scenes in VR

ANOVA					
Observations					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	853.822	2	426.911	3.875	0.024
Within Groups	10135.505	92	110.169		
Total	10989.326	94			

To further investigate how the virtual fire scenes impacted participants' physiological conditions, further Tukey post hoc analysis is reported on Table 6. Tukey can be conducted with as little as two sample comparisons, however, the accuracy and confidence of the outcome yields a higher prediction when the sample size increases.

Table 6 shows that the mean difference is significant at 0.05 alpha level, which indicates that the participants were highly impacted by the Morgue = 6.495 vs Cabin most, followed by the Old House = 5.895 vs Cabin, and the Cabin impacting the least among the three levels of fire scenes.

Table 6. Multiple Comparison Tukey HSD test

Multiple Comparisons						
Dependent Variable:						
Tukey HSD						
(I) Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Cabin	Morgue	-6.49524*	2.612	0.039	-12.716	-0.274
	Old House	-5.895	2.612	0.067	-12.116	0.326
Morgue	Cabin	6.49524*	2.612	0.039	0.274	12.716
	Old House	0.600	2.710	0.973	-5.856	7.056
Old House	Cabin	5.895	2.612	0.067	-0.326	12.116
	Morgue	-0.600	2.710	0.973	-7.056	5.856

*. The mean difference is significant at the 0.05 level.

Conclusion and Discussions

The purpose of the study was to investigate the effectiveness of VR fire training simulation on the untrained future firefighters. Due to the time and equipment limitations, the study reported statistical and observational data for five student participants. Of the three variables: 1-heart rate, 2-respiratory rate, and 3 – the posture from the participants, the latter two did not yield reportable data due to the limited number of participants. However, the researchers discovered that the intensity of virtual reality fire simulation fire scenes, with variable intensity levels of fire, resulted in a significant heart rate elevation between scenes. A negative reaction of untrained/first-timer firefighters may lead to delay in decision making during a critical time and may lead to injuries during duties. One of the limitations, in addition to the number of participants, was the production of the VR environment. Although the various scenes provided significant differences in the outcomes, the researchers believe that the participants were under the impression of a game environment with almost zero safety concerns. Future studies should incorporate realistic scenes in the VR environment to observe the impact on the participants.

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