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Wayfinding in Virtual Reality Serious Game: An Exploratory Study in the Context of User Perceived Experiences

Shafaq Irshad *, **Andrew Perkis** and **Waleed Azam**

Department of Electronic Systems, Faculty of Information Technology and Electrical Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway; andrew.perkis@ntnu.no (A.P.); waleedaz@stud.ntnu.no (W.A.)
* Correspondence: shafaq.irshad@ntnu.no

Abstract: Extended reality (XR) technologies such as virtual reality (VR) provide a promising alternative for training users through serious games (SGs). VR SGs allow people to train in emergency scenarios and improve their likelihood of survival in high-risk situations. Studies have shown that incorporating design elements such as wayfinding cues enhances the spatial knowledge of users in VR. However, the impact of these wayfinding cues on users' psychological and psychometric behaviors needs thorough investigation. An SG was designed to investigate wayfinding cues' psychological and psychometric effects on user-perceived experiences in an immersive VR environment. Thirty-nine participants experienced three variants of the VR SG using Oculus Rift- S. Participants in the control condition were exposed to the VR with no wayfinding cues, and the experimental groups were exposed to VR with static and dynamic wayfinding cues. Results showed that VR SG with wayfinding cues induced less tension, challenge, and negative affects in users' overall perceived experience. Similarly higher positive affects were observed for the experimental groups with wayfinding cues. It was interesting to observe that there were no significant effects of wayfinding on competence, flow, and immersion; however, heart rate was significantly high in the control group. These findings suggest that wayfinding cues can promote the users perceived quality of experience in the VR.

Keywords: virtual reality; serious games; exended reality; training simulations; user studies; spatial information; perception

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1. Introduction

Extended reality (XR) technologies have evolved into ultra-high-definition, immersive displays due to breakthroughs in data acquisition, data transmission, and playback output devices for media content [1,2]. XR technologies such as virtual reality (VR) can now provide more interactive and immersive experiences due to rapid technological advances such as state-of-the-art full-body motion tracking, gyroscopes, motion sensors, stereoscopic displays, and audio [3]. Although VR is primarily focused on entertainment, recent research studies highlight its implications in numerous other fields such as education [4], healthcare [5,6], and training for disaster preparedness of natural hazards such as flooding [7].

Recent research has shown that VR can administer a narrative-rich, high-fidelity environment that administers a fully immersive and interactive experience for serious games (SGs) such as disaster preparedness and evacuation training for hazardous situations [8]. Although VR SGs can be entertaining, their fundamental purpose is to provide training and education to its users. VR-based serious games offer a secure space to conduct training that would be risky and costly in real life [9]. Studies have been conducted to show that the skills learned during a well-designed VR SGs are long-lasting [10] and depend mainly on the efficiency and wayfinding capabilities of participants [11]. Wayfinding capabilities of the VR users can be enhanced by aiding the spatial knowledge through contextual cues [12]. These contextualized VR games can improve behavioral responses, learning outcomes and evacuation preparedness of users [13]. However, the role of contextual cues such as wayfinding in virtual reality environments (VRE) and its influences on user-perceived quality of experience is yet to be thoroughly researched [14].

In the current study, we designed an experiment to investigate the impact of wayfinding cues on users' behavioral and physiological responses using Oculus Rift S head-mounted display (HMD). Thirty-nine participants were presented with VRE of a flooded city and asked to navigate the city to find a safe zone in a timed scenario. Participants were divided into three groups, i.e., a controlled group without any wayfinding cues, an experimental group with static wayfinding cues (directions only), and an experimental group with dynamic wayfinding cues i.e., assistive lights along with directions. It was hypothesized that wayfinding cues would significantly impact players' physiological and psychological behavior in VRE. Our findings suggest that integrating contextual wayfinding cues in VR training simulations can result in effective VR design and enhance users perceived experiences of these applications.

The research article presents a detailed review of existing studies on VRE wayfinding in the next section. Section 3 explains the materials and methods used in the experimental design, followed by a detailed result section. Section 4 discusses the research findings, followed by a conclusion.

2. Related Work

2.1. Virtual Reality Serious Games for Natural Disasters

Floods are one of the most recurring and damaging natural disasters, universally, with adverse aftermaths and economic losses affecting 1.6 billion people worldwide [15]. In the last 20 years, the Center for Research on the Epidemiology of Disasters (CRED) emergency events' database recorded 7348 natural disasters, claiming approximately 1.2 million lives. The majority of these natural disasters were floods and storms, with an average of 44% and 28%, respectively. Numerous hazardous flooding events in Kyushu, Nepal, Indian, and most recent ones in Uttarakhand have repeatedly reminded humans of this imminent threat. Training people for disaster preparedness or emergency evacuation during floods can reduce the risk of injury and provide a better likelihood of survival.

In contrast to traditional disaster preparedness methods such as drills or seminars, extended reality (XR) technologies such as VR have gained prominence for training people at low cost through serious games (SGs) [16,17]. SGs are defined as "digital games that are used for purposes other than entertainment [18]" VR SGs allow its users to experience digitally simulated scenarios that are impossible to be experienced in the real world due to cost, time, and safety.

These VR SGs engage users by providing life-like scenarios, where they can interact with in-game objects, solve challenges, and become familiar with disaster preparedness methods [19] thus developing life-saving skills. Various VR SGs studies have been performed on the use of VR as a procedural training tool and provide empirical evidence on how VR training skills can be transferred to real-world [20]. Researchers [21] have investigated the impact of game-based learning for flood risk management and researched how training-based SGs can support lifelong learning in people.

Several research studies have focused on understanding the underlying concepts and principles of disaster preparedness in VREs. A VR framework for disaster awareness and emergency response training was proposed by Yusuf Sermet et al. [19] which presented a realistic VR gaming environment to increase public awareness, train and evaluate respondents in emergencies using simulated real-time flooding scenarios. Research has shown that participants experiencing a VR simulation of flooding showed increased motivation to evacuate, seek information, and preference to buy flood insurance compared to the other disaster preparedness methods tested [22].

VR simulates a realistic environment in which a person can navigate and interact freely in the virtual environment. When VR is used to create training simulations such as flood evacuation, complex scenarios are formed inside the VRE. In order to guide the

VR users inside these complex representations, effective design strategies incorporating navigational aids such as wayfinding cues are required [23].

2.2. Wayfinding in Virtual Reality Training Simulations

Wayfinding is defined as "the ways in which people orient themselves in physical space and navigate from origin to destination [24]". When people try to find their way to a destination in a foreign environment, they look for external information that will complement their orientation and navigation processes in this unfamiliar environment. When VR training simulations are designed for flood evacuation, it is difficult for VR users to navigate inside the unfamiliar immersive environment.

Researches have shown that when people evacuate flooded areas, their wayfinding capabilities are crucial in determining the efficiency of their evacuation and hence their chances of survival. Therefore, VR environments should be designed to ensure the transfer of flood evacuation knowledge and skills gained in the VRE to the real world by incorporating wayfinding cues [24]. Jerald [25] used the term signifier to describe wayfinding cues by stating that "any perceivable indicator (a signal) that communicates appropriate purpose, structure, operation, and behavior of an object to a user".

Wayfinding has been used extensively in evacuation and navigation experiments, since it creates affordances by prompting human actions [26,27]. Various studies have investigated design, and implementation of navigation processes such as wayfinding cues inside the VRE for training and evacuation applications [28]. Researchers have suggested that VR game designers need to incorporate wayfinding processes in the VR to aid users in navigating the environment. A recent study proposed several wayfinding affordances that need to be incorporated in the VR design to assist users in constructing mental models in virtual environments [29]. Further studies have shown the use of contextual cues such as wayfinding installations, signage systems to improve users' ability to navigate through the complex VR environments [30].

Various risk mitigation institutes across the globe are adapting VR applications to train users in hazardous situations that cannot be portrayed through traditional methods. A recent study proposed two methods to encourage early evacuations during flash floods by implementing environmental or social cues in VR [31]. Results revealed the effectiveness of using VR to promote evacuation during natural disasters. Panos Kostakos et al. [32] used VR wayfinding installations to investigate the effect of wayfinding lights on behavioral, physiological, and psychological outcomes in indoor fire evacuation scenarios. Results showed that wayfinding affordances could be used to reduce cognitive demands, and wayfinding installations along with visual stimulus can also contribute to improved brain wiring connectivity during the game.

In the past, wayfinding studies have been conducted in indoor environments [31,33] and mostly for fire [27,34,35], underground rock-related hazards safety training [33] and earthquake evacuations [10,14]. These researches have [32] suggested that further studies should be conducted to improve the evaluation process for VR evacuation trainings.

Measuring the impact of wayfinding installations on user behavior and improving their effectiveness is a very important task [36]. Although VR training simulations are becoming well accepted because of the cost-effective way of providing training, few studies have used VR experiments to test flood-related behaviors. Similarly, the validity of user behaviors in VR SGs is not widely researched [31] and is critical as VR applications are increasingly being used for training. Furthermore, the methodologies to measure these VR applications' emotional impact and influence need to be developed and tested.

We used a mixed-method approach to fully capture the impact of wayfinding cues in VRE to gain comprehensive understanding of user behaviors inside the VRE. The research question addressed was: What is the impact of wayfinding cues on users physiological signals and perceived quality of experience in a VR SG for flood evacuation training? Based on the research question, we hypothesized that implementing wayfinding cues in the VR-SG will result in a lower heart rate (HR) and enhanced user perceived quality of experience. Materials and methods used to investigate the emotional impact and influence of wayfinding cues in VR SG is presented in the next section.

2.3. Materials

2.3.1. Participants

Thirty-nine participants (13 females and 26 males; aged 18–54) volunteered to take part in the study. 20.51% of the participants were between the age group of 18–51. Most of the participants (61.53%) were aged between 25 and 34 years old and rest were older than 34. A total of 69.23% of the participants had intermedia computer skills and 23.08% of participants had expert level computer skills. 69.23% of participants had not experienced VR before, however 30.77% percent of the participants had experienced it once or twice before taking part in the study. All the participants were given detailed instructions and thorough demonstration despite their computer and VR skills. Participants with visual disturbances such as colour blindness (color vision deficiency) were not included in the study however, since Rift HMD allows for a comfortable viewing with glasses participants with farsightedness, near-slightness were included as mentioned in Rec. ITU-T G.1035 (05/2020) [37].

2.3.2. Equipment

In this study, Oculus Rift S was used for the VR gameplay. The high level of accuracy and precision (display resolution of 1280 × 1440 pixels per eye) combined with the low cost of the Oculus Rift S HMD and its use of inside-out tracking made it a viable option to be used in this experiment [38]. Five cameras inside the Oculus VR headset enable inside out tracking by tracking and translating the objects to 3D position in real time [39]. Studies show that Oculus Rift S is a powerful tool for research and provides a greater degree of immersivity and reduces motion sickness [40]. The experiment was run on an Asus ROG STRIX gaming laptop with Intel(R) Core(TM) i7-8750H processor with NVIDIA GeForce GTX 1070 graphics card. Figure 1 shows the equipment used in the study.

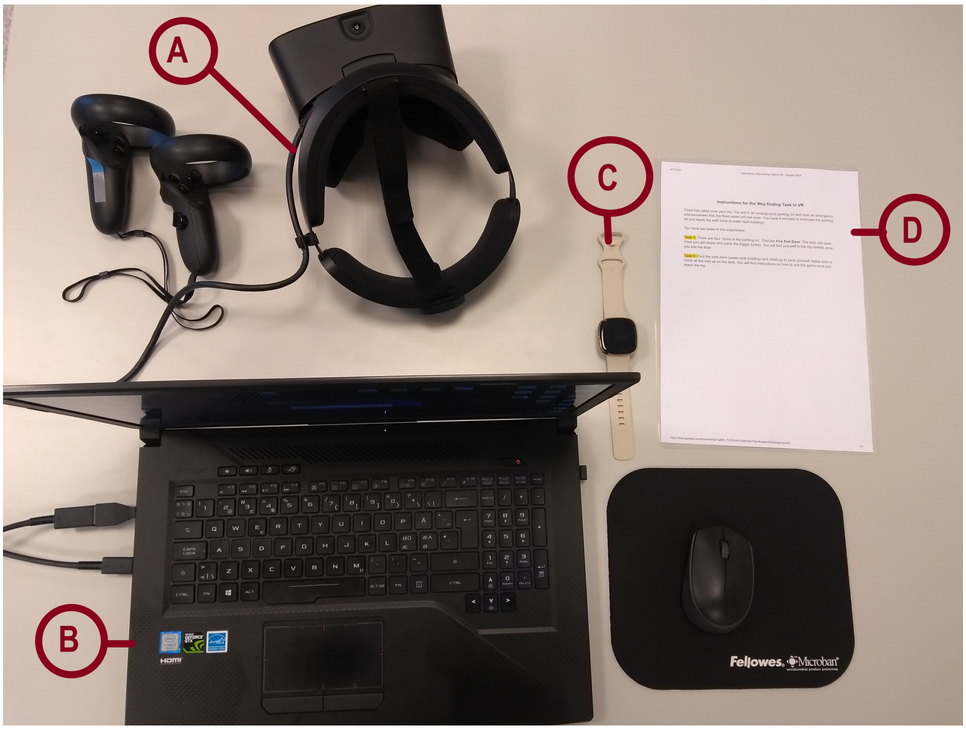


Figure 1. Figure illustrating the equipment used in the experiment: (**A**) Oculus Rift S head-mounted display (HMD) (**B**) Gaming laptop with GeForce GTX 1070 graphics card to run the virtual reality (VR) application (**C**) Fitbit Sense for measuring the HR (**D**) Instructions to perform the tasks and detailed manual to use the VR HMD.

2.3.3. Virtual Reality Environment

The VR training simulation used in this project was developed under a Research project titled “World of Wild Waters” (https://www.woww.no/, accessed on 19 July 2021). This disaster training and emergency preparedness project is part of NTNU’s digital transformation initiative to reduce the casualties and effects of the disaster. The VRE serves as an assessment tool to measure the impact of wayfinding cues on users’ perceived quality of experience in a serious game setting.

Unity 3D (https://unity.com/, accessed on 19 July 2021). was used to design, develop and render the virtual reality environment using several open-source libraries as shown in Figure 2. In order to ensure proper content delivery during the VR experience, VRE was a development based on the recommendations of ITU-T G.1035 [37]. Spatial audio through Oculus Spatializer Plugin [41] was implemented for a fully immersive audio experience. It allows pinpointing sounds in the VRE accurately. The VRE was deployed on the Oculus Rift S using a gaming laptop. The participants were exposed to the custom designed VRE. Schematics of the VRE experiment are illustrated in Figure 2.

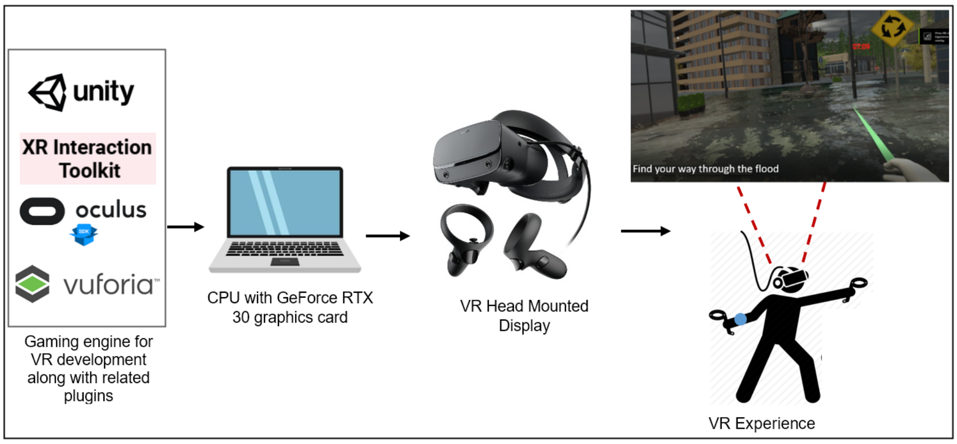


Figure 2. Figure shows the schematics of the experiment. VR SG was developed with unity game engine and deployed on Oculus Rift S via high performance gaming PC.

Participants were exposed to a VRE with an underground parking lot and several routes to navigate through the game, as shown in Figure 3. Once the users were inside the VRE, they found themselves in a flooded parking lot. Participants could hear the sirens and an emergency flood warning and were asked to evacuate immediately by performing two tasks i.e.,

1. Exit the building through the emergency exit door (see Figure 4A)
2. After evacuating the building, reach a safe zone (see Figure 4B) through the flooded city to complete the evacuation process.

In the VRE, the participants could navigate through the city both by physical locomotion and teleportation using HMD controllers. Both types of locomotion were implemented to enhance immersion and avoid simulator sickness [42]. Locomotion techniques were used because of their advantage over constant (walking-like) motion for the estimation of distances, which is an important basic spatial measure in navigation [43].

The level of flooded water was kept lower, so it was easier for the participants to move through the VRE. Underwater effect with partial submersion and water physics were implemented to allow the participants to experience as if they are navigating through real water using Crest water system (https://assetstore.unity.com/packages/tools/particles-effects/crest-ocean-system-urp-141674, accessed on 19 July 2021). A unity plugin called Enviro sky manager was used to implement a dynamic weather system for realistic thunder and rain effects. A time limit of 8 min was given to the participants to complete the tasks. The timer was visible to the participants at all times, as shown in Figure 5.

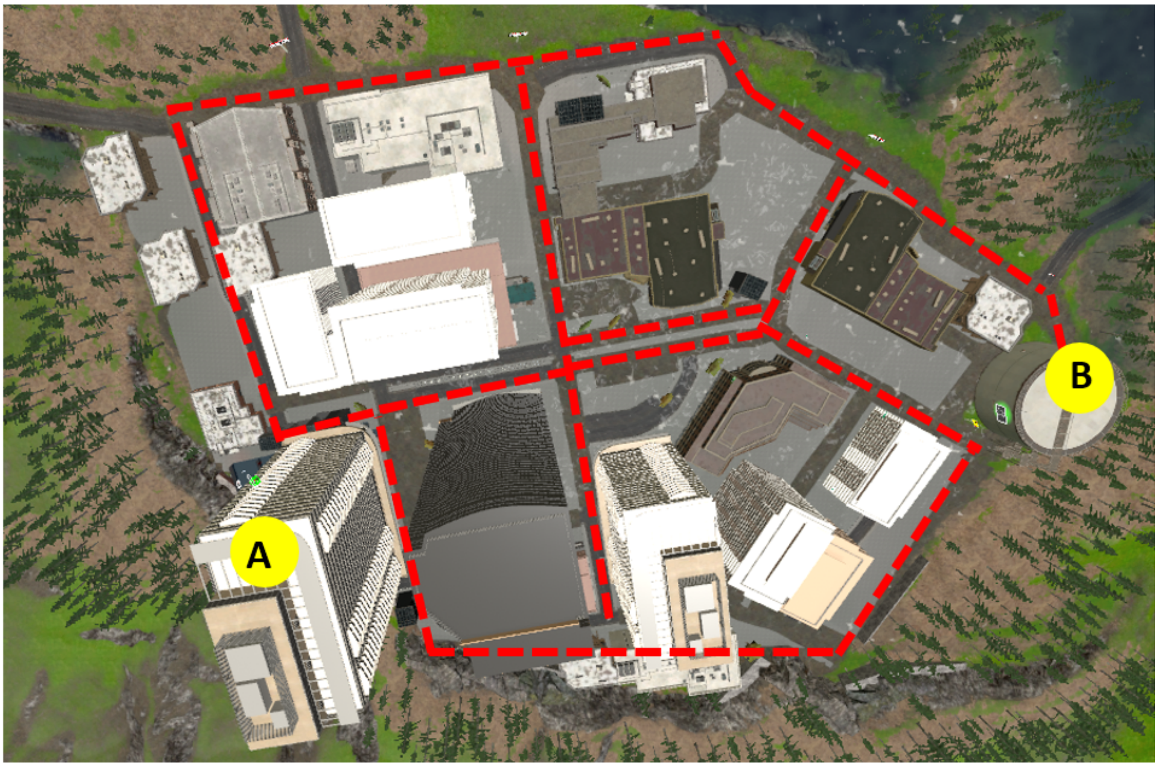


Figure 3. The figure illustrates an aerial view of the VRE. Point A indicates the location of the underground parking lot (starting point of the VR game), and Point B indicates the safe zone (the endpoint of the VR game). Red markings highlight the possible navigation routes that could be followed to complete the evacuation task.

(A) (B)

Figure 4. (**A**) Figure illustrates the view of the parking lot in the VRE. Users were asked to exit the parking lot like their first task. (**B**) The figure illustrates the safe zone in VRE. Participants were asked to evacuate the flooded city and reach the safe zone in under 8 minutes to save themselves from the flood.

Figure 5. Detailed view of the VRE as seen by the participants inside the HMD. A timer was displayed in front of the participants while they navigated through the city.

Three variations of the VRE were made in order to examine the impact of wayfinding cues in detail, and only wayfinding cues were varied in the three VREs. These three VRE demonstrated the three experimental conditions as shown in Table 1.

Table 1. Table presents the three experimental conditions investigated with and without wayfinding cues.

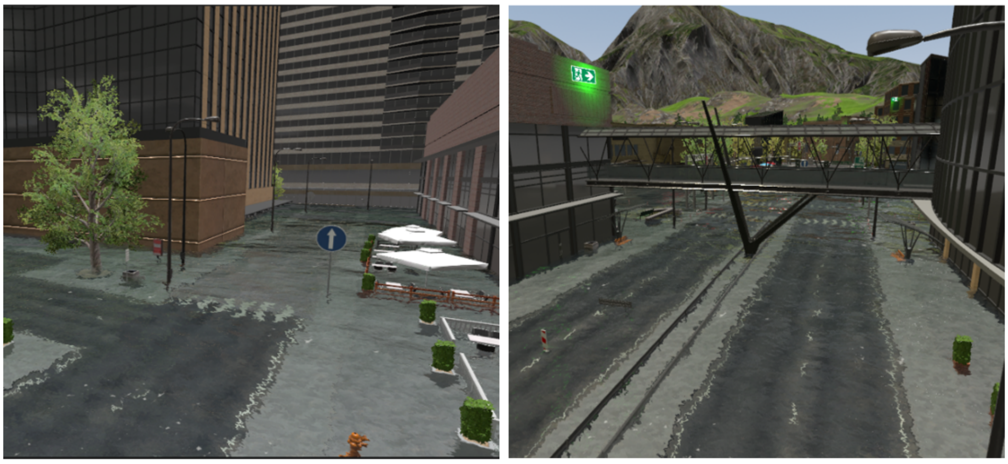
No	Condition	Variations
1	Control Condition (CC)	No wayfinding cues
2	Experimental Condition 1 (EC1)	Static wayfinding cues
3	Experimental Condition 2 (EC2)	Dynamic wayfinding cues with visual stimulus

There were no wayfinding cues implemented in the VRE for the control condition (CC). Static wayfinding cues i.e., signage, were implemented in the first experimental condition (EC1) as shown in Figure 6A. In the second experimental condition (EC2), dynamic wayfinding cues with visual stimulus were implemented as shown in Figure 6B. The design of wayfinding cues such as flashing LED lights were implemented following evacuation design guidelines [28,44,45]. We tested the VREs using a between-group design and an equal number of participants (n = 13). Details of the procedure are given in Section 2.5. To measure the impact of wayfinding on user perceived experiences, physiological and psychometric evaluations were recorded, as explained in the next section.

2.4. Evaluation Measures

2.4.1. Physiological Evaluation

Heart-rate (HR) measurements were recorded for all 39 participants throughout the experiment using the latest Fitbit Sense smartwatch. Fitbit Sense was used to measure the HR with a multi-path optical heart rate sensor that delivers PurePulse 2.0 (https://www.fitbit.com/global/us/products/smartwatches/sense, accessed on 19 July 2021) as shown in Figure 7. It offers continuous heart rate tracking and tracks heart rate variability (HRV), which varies between each heartbeat. The Fitbit devices have been used in several studies and shown to produce consistent and reliable results [46,47]. Several studies have reported the computational precision of HR through a photoplethysmogram (PPG) sensors used in Fitbit sense [48].



(A) (B)

Figure 6. (**A**) Figure shows the directional wayfinding cues used in EC1. Signage system was implemented throughout the VRE to guide the users to safe zone. (**B**) Figure shows the wayfinding cues with visual stimulus used in EC2.

Figure 7. Fitbit HR sensor showing multi-path optical heart rate sensor.

2.4.2. Psychometric Evaluation

A post-test game experience questionnaire (GEQ) was used [49,50] to collect user perceived experiences after the VR experiment. GEQ is widely used in assessing the game experience of end users in virtual environments [51] and contain four modules: (1) the core questionnaire; (2) the social presence module; (3) the post-game module; (4) the in-game module.

All modules are meant to be administered immediately after the game session has finished. The in-game experience core module probes the players' feelings and thoughts while playing the game and was used in this study. It measures game experience as scores on seven components i.e., Immersion, Flow, Competence, Positive and Negative Affect, Tension, and Challenge [49], as shown in Table A1. Details of the results collected from the modules is presented in the result section.

In addition to the GEQ, we used a pre-study questionnaire to gather demographic information about participant age, gender, nationality, and education. The questionnaire also measured sociodemographic information such as familiarity with VR games, computer skills, and familiarity with evacuation drills. The questions categorized in relevant categories are presented in Appendix A Table A1.

Participants rated their experience independently on a category scale using the Absolute Category Rating (ACR) System as recommended by ITU-T P.910 [52] as shown in Table 2. Player competence was measured using five questions. Immersion was captured through 6 questions. The flow was captured by measuring attributes. Tension was measured using players' annoyance, irritability, and frustration while playing the game.

Challenge was measured through constructs like the challenge, time pressure, and effort required by the player while experiencing the VRE.

Table 2. ACR used in this study.

Absolute Category	**Rating Scale**			
1	2	3	4	5
not at all	slightly	moderately	fairly	extremely

2.5. Procedure

Interested participants joined a volunteer list by signing up for the experiment. Information about their age, gender, educational background, visual disturbances, and availability to attend the experiment was collected. Selected participants were informed through email and, upon confirmation, notified about the venue and time. The experiment was held at Sense-IT lab at the Department of Electronic Systems, Faculty of Information Technology and Electrical Engineering, NTNU in Norway.

On the day of the experiment, participants were welcomed in the lab and briefed about the COVID Standard Operating Procedures (SOPS) they were supposed to follow. Once comfortable, the participants signed the consent form and were informed about the scope of the experiment and the content of the VR SG. Participants were asked to wear the Fitbit sensor, and the baseline HR reading was recorded. Next, they were presented with written instructions on using the Oculus Rift S and its controllers.

Participants played a short demo VR game to learn to use the Oculus Rift S HMD's controllers for locomotion and teleportation inside the VRE. To ensure participants' safety, a Guardian Boundary was set up inside the Oculus around the lab's play area of 4 m $\times$ 6 m. The virtual guardian boundary helped the participants stay inside the designated play area and appeared inside the VR when the participants crossed the designated area.

After completing the demo, participants were randomly placed into one of the three experimental conditions(CC, EC1 or EC2). Before starting the task, participants were briefed about the tasks, both orally and in written form, by the experimenter. They were shown the map of the game before and during the game . Details of the tasks given to the participants was as follows:

Flood has taken over your city. You are in an underground parking lot and hear an emergency announcement that the flood water will rise soon. You have 8 min to evacuate the parking lot and reach the safe zone. You have two tasks in this experiment.

- Task 1: There are four doors in the parking lot. Find the Fire Exit Door. The door will open once you get closer and press the trigger button. You will find yourself in the city streets once you exit the door.
- Task 2: Find the safe zone (water tank building) and climb up to save yourself. Make sure to climb up on the tank. You will find instructions on how to quit the game once you reach the top.

Participants put on their HMD and played the VR SG as shown in Figure 8.

Figure 8. Participant wearing Fitbit HR sensor and Oculus Rift S HMD attached with the high performance gaming PC during the experiment.

After the participants finished the VR experience, their HR was re-recorded using the Fitbit. Participants were asked to complete the GEQ. HR device was removed after the last step. It took approximately forty minutes (or less) for the whole experiment to be completed. Participants were compensated with a cinema ticket for their time and effort. Results from the study are presented in the following section.

3. Results

3.1. Physiological Evaluation

Figure 9 demonstrates the time series scatter graph of HR mean values between the three experimental groups. Preliminary inspection of the graph illustrates higher HR values (mean = 97.69) in the control group with no wayfinding during the VR experience, i.e., the section marked with red dotted lines. Participants in the experimental group with static and dynamic wayfinding exhibited a similar trend, with mean values of 80.5 and 79.8, respectively (Table 3). ANOVA was applied to examine any significant effects in the three groups, and results showed that the HR for the controlled group with no wayfinding was significantly higher, $p < 0.05$ (see Table 4) than the experimental groups.

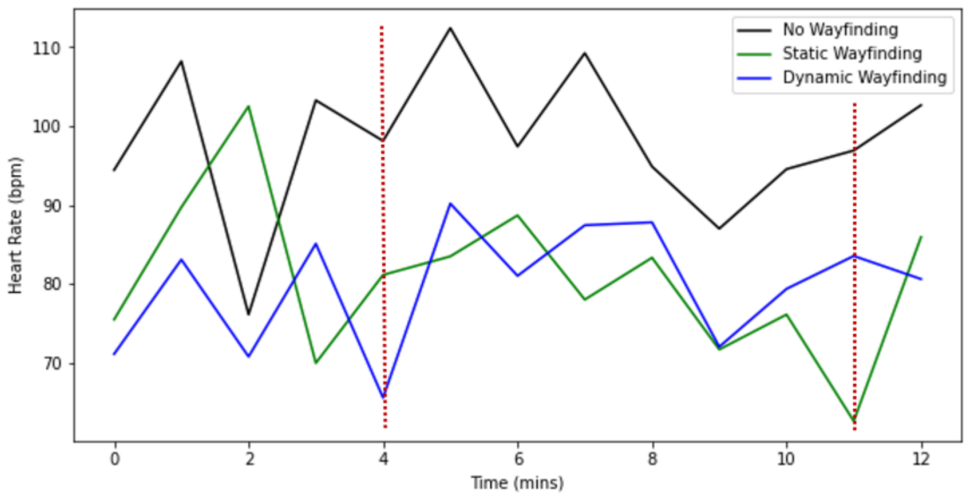


Figure 9. The graph illustrates HR data (beats per minute) recorded using an advanced HR sensor during the training and testing phase. The x-axis shows time elapsed in minutes. HR data between the red checkpoints exhibit the HR during the actual VR experience for the three groups.

Table 3. Mean scores of HR for the three groups.

	Control Condition (n = 13)		Experimental Condition 1 (n = 13)		Experimental Condition 2 (n = 13)	
	Means	**SD**	**Means**	**SD**	**Means**	**SD**
Heart Rate	97.69	9.60	80.53	10.134	79.83	7.57

Table 4. Results from one-way Analysis of Variance (ANOVA) for the HR measurements of the three groups.

		Sum of Squares	df	Mean Square	F	Sig.
Heart Rate	Between Groups	2660.839	2	1330.419	15.818	0.000
	Within Groups	3027.957	36	84.110		
	Total	5688.796	38			

3.2. Psychometric Evaluation

Game experience questionnaire [53] was issued to record the psychometric data in the three groups (n = 39), i.e., one control group (CC) and two experimental groups (EC1, EC2) where each group had 13 participants. A one-way analysis of variance (ANOVA) was performed to compute the effect of wayfinding cues on the users' perceived quality of experience using seven metrics [53] (Appendix A Table A1).

Control group with no wayfinding cues exhibited a significant main effect on ratings of feeling *challenged*, $F(2,36) = 4.907$, $p = 0.013$. Post hoc comparisons using the Tukey HSD test on feeling challenged indicates that the mean score for the CC (M = 2.5846 SD = 0.51291) was significantly different from the EC1 condition (M= 1.8769 SD = 0.58045). However, the EC1 (M = 2.3077 SD = 0.64091) did not significantly differ from CC and EC2 conditions as shown in Table 5. These results indicate that the control group with no wayfinding perceived the VRE as challenging compared to the two experimental groups.

The test also revealed a statistically significant difference in mean scores of tension between at least two groups ($F(2,36) = 15.700$, $p < 0.001$). Tukey's HSD test for multiple comparisons found that the mean value of tension was significantly different between CC and EC2 ($p < 0.001$, 95% C.I. = [0.6490, 1.6490]). There was no statistically significant difference between the experimental groups ($p = 1.000$). These findings reveal that the level of tension was higher in the group with no wayfinding cues. However, there was no difference in the level of tension or annoyance in the two experimental groups with static and dynamic wayfinding installations.

For positive and negative affect, the significance level of $p < 0.05$ was observed for the three groups, and mean scores for positive affect and negative affect in CC were significantly different from EC2 (see Table 5). Although there was a difference in means for immersion, flow, and competence, ANOVA did not exhibit significant main effects of feeling immersed, competent, and inflow during the VRE as shown in Figure 10.

Table 5. Mean scores of GEQ metrics for the three groups.

	Control Condition (n = 13)		Experimental Condition 1 (n = 13)		Experimental Condition 2 (n = 13)	
	Means	**SD**	**Means**	**SD**	**Means**	**SD**
Challenge	2.58	0.51	2.30	0.64	1.87	0.58
Tension	2.10	0.59	0.79	0.73	0.79	0.71
Positive Affect	2.44	0.68	2.78	0.77	3.27	0.46
Negative Affect	1.46	0.49	0.73	057	0.44	0.44
Competence	2.33	1.06	2.21	0.82	2.70	0.50
Immersion	2.66	0.69	2.91	0.72	3.03	0.51
Flow	3.01	0.51	2.70	0.60	2.67	0.75

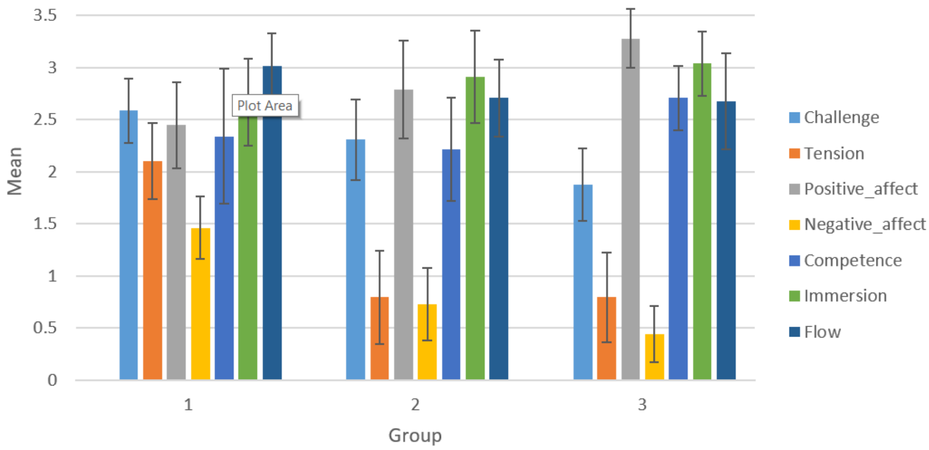


Figure 10. Clustered bar mean of GEQ items administered in this study.

4. Discussion

Recent developments in immersive multimedia technologies have allowed VR SGs to be used in training people for disaster preparedness. The present study was designed to compare the perceived experiences of participants in an immersive VR training simulation depicting a stressful flooding scenario by controlling the experimental conditions with static and dynamic wayfinding cues. Three groups of participants played the same VR game, with and without wayfinding cues guiding them to the safe zone. We hypothesized that participants in the experimental group with dynamic wayfinding (assistive lights and signage) would have a higher perceived experience than those in the control group. Furthermore, we hypothesized that participants in the control group would exhibit higher heart rates as compared to the two experimental groups due to a lack of wayfinding cues. We used Fitbit Sense to perform a physiological evaluation through HR measurements and a post-test GEQ questionnaire for psychometric evaluation to measure the user-perceived quality of experience inside the VR game.

4.1. Effects of Wayfinding on Physiological Evaluation

Results from the ANOVA test demonstrates that the HR values were significantly higher for the control group with no wayfinding while lower for the two experimental groups with wayfinding cues. These findings suggest that the presence of wayfinding cues in EC1 and EC2 may have helped the users to create spatial knowledge of the immersive VRE while navigating through the environment, thus lowering their cognitive workload [30,54]. A related study supports these findings [32] in which the HR of 17 users in two groups was observed during a navigation task in an underground tunnel. The study found HR to be significantly higher in the experimental group exposed to directional signs in the underground tunnel. Physiological measures observed in the present study suggest that implementing wayfinding cues in VR training simulations can positively create mental models inside users' brains, thus lowering the cognitive load and improving their perception of the immersive VR system.

4.2. Effect of Wayfinding on Psychometric Evaluation

Effects on challenge: Challenge was used to measure the impact of wayfinding cues on the user-perceived experience of VR application used in this study, since the challenge is a crucial metric to evaluate the gameplay experience [55]. Wayfinding cues were found to substantially elevate the element of challenge in controlled conditions, as shown in Table 6. The mean values for the challenge were significantly lower for EC2 with dynamic wayfinding cues as compared to the other two conditions. Our findings are consistent with the existing research, which states that players use emotional and cognitive efforts to understand the disposition of the game and solve the challenges presented to them [56]. Since

EC2 in this study presented the participants with wayfinding cues in the VR environment, their cognitive ability to perceive the sense of direction inside the VR was better; hence they felt less pressured. Similarly, they had to put less effort and perceived the overall experience to be less challenging as compared to the CC with no wayfinding. For EC1, the mean values of challenge were between CC and EC2 and can be explained by the fact that static cues were used in the VR experience and didn't grasp the participants' attention when they were stressful in the VRE.

Table 6. One-Way ANOVA results showing the significance of wayfinding on users perceived behavior.

		Sum of Squares	df	Mean Square	F	Sig.
Challenge	Between Groups	3.307	2	1.653	4.907	0.013
	Within Groups	12.129	36	0.337		
	Total	15.436	38			
Tension	Between Groups	14.821	2	7.410	15.700	0.000
	Within Groups	16.991	36	0.472		
	Total	31.812	38			
Positive Affect	Between Groups	4.537	2	2.269	5.286	0.010
	Within Groups	15.452	36	0.429		
	Total	19.990	38			
Negative Affect	Between Groups	7.176	2	3.588	13.878	0.000
	Within Groups	9.308	36	0.259		
	Total	16.484	38			
Competence	Between Groups	1.707	2	0.853	1.233	0.303
	Within Groups	24.917	36	0.692		
	Total	26.624	38			
Immersion	Between Groups	0.927	2	0.464	1.090	0.347
	Within Groups	15.321	36	0.426		
	Total	16.248	38			
Flow	Between Groups	0.911	2	0.455	1.122	0.337
	Within Groups	14.609	36	0.406		
	Total	15.520	38			

Effects on Tension: Feelings of annoyance, irritation, and frustration during the gameplay can lower the quality of perceived experience in users. VR serious games should be designed in such a way to lower the feelings of annoyance and tension [57] to improve the perceived user experience. Our study found that the level of tension was significantly lower in experimental groups, i.e., EC1 and EC2, compared to the control condition with no wayfinding. Since the VRE was kept consistent in all groups except for the wayfinding cues, we can deduce that the participants in these groups perceived the VR simulation as less annoying to navigate due to wayfinding. The results are supported via a study by Lin et al. [34]. Other research studies [34,58] have demonstrated similar results of lower tension and annoyance in spatially oriented VR applications in various domains.

Effects on Positive and negative Affects: Wayfinding cues were found to considerably elevate the positive affects and lessen the negative affects on the users in the VR environment [34]. We measured the positive affects through their level of enjoyment, contentment, fun, and happiness. Positive affects were highest (mean = 3.27), and negative affects were lowest (mean = 0.44) in the EC2 with dynamic wayfinding as compared to the other two groups (see Table 5).

Effects on Competence: Effects of wayfinding on competence were also observed. Although there were some differences in the mean values, our results did not show any significant effects of these three metrics on the participant's perceived experience in VR. All the participants felt successful and competent while playing the VR simulation and reached their target.

Effects on Immersion: Various studies have shown that immersion inside a VR environment can be increased by increasing spatial affordances [59,60]. However, our study showed no significant differences in immersion in all the groups, although the mean value of immersion was slightly higher in the EC2 condition. These results are in alliance with a study that explores the effects of wayfinding affordances in underground facilities during a fire emergency [32].

Effects on Flow: The flow inside a game is attributed to participants' concentration in the game, how they forget about the outer world and things around them, and the loose notion of time. We observed no significant differences in the three groups for flow measures. However, the mean value of flow in CC (Mean = 3.01, see Table 5) was higher than the experimental conditions. This abnormal increase in the flow in the no-wayfinding control condition can be explained by the fact that there was no guidance inside the VR. Hence, participants were more concentrated on the end goal. They lost the notion of time and surroundings since they were in a stressful situation (timer, sirens, and announcements in the background) and wanted to exit immediately.

The effects of immersion and flow did not show any significant differences in the study on VR training in stressful situations and align with our results [61]. This can be explained by the fact that VRE was kept consistent for all the groups and only wayfinding cues were varied [62].

This particular study investigates user behaviors in both indoor and outdoor VR settings (Task 1 and Task 2 in our study; see figure for more details Figure 4). We can conclude that carefully installed cues in VR training applications can help reduce tension in users, thus improving their overall perceived experience. The present study advances the understanding of wayfinding on users' psychological and psychometric behaviors and provides essential design implications. Further research could be done to explore the impact of wayfinding on simulator sickness in VR and how it correlates with the physiological and psychometric metrics. The findings can be used to support building better VR SGs for evacuation training.

5. Conclusions

The present study aimed to investigate the impact of wayfinding cues in a VR SG for disaster preparedness. Three groups of participants were asked to perform two tasks while navigating through a flooded VR simulation. Physiological and psychometric evaluation was performed to observe the effects of wayfinding cues on their HR and perceived VR experience. We found statistically significant differences in the HR of participants in the two experimental conditions with wayfinding cues (EC1 and EC2) compared to controlled conditions with no wayfinding cues (CC). However, there was no significant difference between EC1 and EC2. In terms of user-perceived quality of experience, we found that participants found it more challenging and tension-inducing to navigate through a flood simulation without wayfinding cues. The present study suggests that contextual cues are an essential element in VR SG design, and carefully introducing these contextual cues can increase the affordance of end-users and thus their overall perceived experience. This may improve the users' performance and learning outcomes from VR training simulations. Future studies may attempt to use advance physiological evaluations, such as electrodermal activity, and in depth analysis to better understand the relationship between immersive environments, training, and affordances.

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Institutional Review Board Statement: The experimental study followed a strict protocol developed based on NTNUs standard ethics regulations, especially for experiments in XR involving human participants. The Research protocol considers the ethical requirements for the experiment, including privacy issues. The research protocol was evaluated and approved by the NTNU Sense-It team leader A. Perkis on 15 July 2020 under project number 81771250. The evaluation concludes that no formal approval is required from the NTNU ethics committee. The privacy issues are taken care of by the Information Sheet and the participant consent form.

Informed Consent Statement: Written Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Dataset generated during the study is avalible at https://github.com/shafaq41/VR_wayfinding accessed on 19 July 2021.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

XR	Extended reality
VR	Virtual Reality
SGs	Serious games
HMD	Head mounted Display
VRE	Virtual Reality Environments
CRED	Center for Research on the Epidemiology of Disasters
HR	Heart Rate
CC	Control Condition
EC1	Experimental Condition 1
EC2	Experimental Condition 2
HRV	Heart Rate Variability
GEQ	Game Experience Questionnaire
ACR	Absolute Category Rating
SOPS	Standard Operating Procedures
ANOVA	Analysis of Variance

Appendix A. GEQ Questionnaire

Table A1. Post-Test GEQ Questionnaire.

	Questions	
Competence	Q2	I felt skilful
	Q10	I felt competent
	Q15	I was good at it
	Q17	I felt successful
	Q21	I was fast at reaching the game's targets
Immersion	Q3	I was interested in the game's story
	Q12	It was aesthetically pleasing
	Q18	I felt imaginative
	Q19	I felt that I could explore things
	Q27	I found it impressive
	Q30	It felt like a rich experience
	Q5	I was fully occupied with the game
	Q13	I forgot everything around me

Table A1. *Cont.*

Questions		
Flow	Q25	I lost track of time
	Q28	I was deeply concentrated in the game
	Q31	I lost connection with the outside world
Tension	Q22	I felt annoyed
	Q24	I felt irritable
	Q29	I felt frustrated
Challenge	Q11	I thought it was hard
	Q23	I felt pressured
	Q26	I felt challenged
	Q32	I felt time pressure
	Q33	I had to put a lot of effort into it
Positive Affects	Q1	I felt content
	Q4	I thought it was fun
	Q6	I felt happy
	Q14	I felt good
	Q20	I enjoyed it
Negative Affects	Q7	It gave me a bad mood
	Q8	I thought about other things
	Q9	I found it tiresome
	Q16	I felt bored

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