Virtual and Augmented Reality for Community Preparedness for Disasters [Part II]

New York University
Centre for Urban Science + Progress
Capstone Project Report

Domain

Infrastructure

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Policy Recommendations

Implement a tiered flood alarm system based on water level risk.
Enhance public awareness and conduct regular flooding drills.
Utilise VR for immersive disaster preparedness training and testing.

Keywords

Virtual Reality, Urban Flooding, Human Behavior, Disaster Preparedness

Abstract

Over the last decade, floods have caused over 100 loss of lives per year according to web data; attention is mainly paid to urban flooding because of the higher concentration of population and limited escape routes, yet due to the difficulty of obtaining data during disasters there is a deficit of analyses on human behaviour under flooding. With the advantages of modern VR technology, this project aims to create a virtual reality environment that can simulate the urban flooding process and collect human behaviour data during the disaster. With a VR environment and VR device, this project conducted a human behaviour study to gather data on participants' awareness of flood risks and evacuation choices. Through experiments, this project conducted a preliminary analysis of human behaviour in urban flooding and found that people's awareness of disaster preparedness needs to be improved. The realism of the VR-simulated floods has been justified in experiments, and it has the prospect of being used in actual disaster preparedness. In addition, this project explored the impact of different factors on people's escape choices and proposed policy recommendations to help improve the disaster preparedness of citizens.

Keywords: Virtual Reality, Urban Flooding, Human Behavior, Disaster Preparedness

1. Introduction and Problem Definition

Flooding is a pervasive and destructive natural disaster that increasingly threatens communities worldwide due to climate change and population growth. On September 1, 2021, New York City experienced a 500-year flood brought on by Hurricane Ida, causing total damages of more than 50 million dollars and 43 fatalities in NJ and NY. Such events highlight the urgent need to raise public awareness of flooding risks to reduce their damaging effects and improve disaster preparedness.

The development of Virtual Reality (VR) technology has provided a practical and effective means for simulating and visualizing real-world scenarios. By engaging users in an immersive and interactive learning experience, VR supports the analysis of various human behaviours in virtual situations. In this study, we recorded human behaviour in a virtual simulation of an urban flooding disaster, utilizing VR technology as a safe and efficient means of collecting numerical data on the impact of flooding on individual responses.

Previous methods of disseminating information related to flooding, such as news reports and pamphlets, only provide a generalized impact assessment. To gain a more nuanced understanding of the risk to safety and well-being associated with the urgency of evacuation or other necessary precautions related to flooding, we conducted an interactive and immersive experiment in VR. This experiment specifically observed people's evacuation choices and ability to judge safe water levels in different scenarios. Results from these observations provide necessary insight into the various factors of disaster impact on human reactions, such as different views, light conditions, and warning methods. This work produces a comprehensive analysis that could improve disaster management and testing for future disasters if utilized by relevant government departments.

2. Literature Review

Virtual reality (VR) is a valuable and powerful tool in various fields, such as disaster research, risk communication, and education. In particular, its application in disasters has been mainly of interest due to its unique ability to simulate and study the impacts of flood events, enhance public awareness, and improve disaster preparedness. Several studies have shown to investigate the effectiveness of VR simulations regarding risk perception and decision-making, with results providing valuable insights into the impact of this technology. The effects of using VR as a risk communication tool by Wang et al. (2019) and a VR fire simulation evacuation experiment by Kinateder et al. (2013) emphasize VR's ability to elicit realistic emotional responses and behavioural reactions. It supports the idea of collecting human behaviours in simulated flooding.

Previous works also examine the effect of different variables on human behaviours under virtual floodings. Fujimi and Fujimura (2020) demonstrated that the changing views of flooding in the virtual environment influenced participants' evacuation decisions. The study also suggested that providing more information cues in the virtual environment could lead to earlier evacuation decisions in real-world scenarios. In Bernardini et al. (2020), water levels have proven to affect the speed of movement during flood evacuation, and safe water levels for successful evacuation have been noted.

3. Experiment Setting and Data Collection

The Unity 3D engine was utilized in the experiment to simulate flooding using pre-built 3D models from the Unity assets store. These assets included buildings, roads, streetlights, and other elements to attain high realism and provide users with a familiar virtual experience. A flat plane with bump mapping techniques was used to simulate a realistic water surface, with its wave effect controlled by a controller supervised by the project supervisor.

In each trial, participants were asked to indicate, with various conditions, when they feel the water depth is in the following stages: 1. Abnormal, 2. Dangerous, 3. Difficult enough to escape. In the above three steps, users will say “abnormal”, “danger”, and “escape” in sequence. The corresponding water depth and related conditions were recorded when they indicated each stage.

For each trial of the experiment, participants will experience:

- different lights: day and night
- views: walking view and driving view
    - Walking view: users can move horizontally in the virtual world.
    - Driving view: users will sit on a chair in the real world. In the virtual world, users will sit in a car.

Figure 1: different views in experiment

- 3 warning methods: no-notice, with voice broadcast, and with alarm notice
    - No-notice: users will not receive any additional information and can only make judgments based on the scene observed by their eyes.
    - With voice broadcast: users will hear the voice broadcast “New York is raining today” at the beginning of flood.
    - With alarm notice: users will hear a sound of sirens at the beginning of flood.

Therefore, a trial will contain up to 2 * 2 * 3 = 12 different conditions.

4. Methodology

The methodology employed in this project involves developing and implementing a virtual reality simulation using the Unity 3D game engine and using VR to observe people's evacuation choices based on the simulated flooding process. The VR simulation aims to recreate realistic flood scenarios and provide users with an immersive and interactive experience to enhance their understanding of flooding risks and disaster preparedness.

4.1. Rationality

The methodology of using VR to simulate flooding disasters and observe human behaviour is rational according to participants' feedback as the following:

1. The city scene modelling is realistic enough, and most users feel like walking on the streets of a big city like New York City.

2. The realism of the rain process, background sounds, and the alarm is sufficient. When a flood occurs, subjects can experience a certain level of tension and fear, ensuring the experiment's effectiveness.

3. The operation is simple. Subjects only need to use five buttons on a controller to complete all functions, including starting/stopping the rain, switching between day and night, walking, and entering/exiting vehicles.

4.2. Limitations

Current settings still have certain limitations, including technical constraints and challenges.

1. The water level changes in increments of 0.01 meters. One can significantly feel the stepwise increase in water level.
2. Interactive operations, such as walking and driving, have limitations due to control constraints within the VR environment. For example, walking in the VR environment is limited to using the joystick on the controller, and the subject cannot work around it, and the vehicle is fixed.

3. Bugs and technical issues arose, such as walking through walls, affecting the overall user experience.
4. The experiment needs to be more automated. Due to the lack of development experience and time, the warning methods' playback and the water depth recording are manually done, which needs to be more convenient.
5. Some hardware problems exist. The headset of Oculus Quest 2 is too heavy, affecting the experience.
6. There are frequent issues of computer crashes or device overheating due to the high-performance requirements of the VR environment.
7. Due to time and technique constraints, there needs to be more data volume. The projects conducted a total of 12 rounds of experiments. Each round of experiments included 12 different scenarios and collected 144 data points.

4.3. Data Analysis Method

For data analysis, we divided the data set into two categories for comparisons: cross-condition and same-condition. To ensure a fair comparison of the different views, we normalized the data using the average view heights for each state. The average view heights for the conditions being compared were 1.5m for the driving view and 1.77m for the walking view. We employed the Kolmogorov-Smirnov (KS) test, an effective nonparametric method for comparing two samples. For cross-condition p-value, the KS test was applied to compare data from conditions i and i+1, i+2, etc. For same-condition p-values, the KS test was used on the data from the same state split according to the user. To decide whether any observed differences were statistically significant, we used a confidence threshold of 0.05. Our data labels were specific for different view types, light conditions, and notice situations. The analysis aimed to understand the perception of danger and evacuation under different conditions. It also tried to make sense of the effect of varying warning methods and other types of behaviour under different light conditions.

5. Result

For analysis, 12 rounds of experiments were conducted, and 144 data records were collected. For the data label, View 0 stands for walking view, View 1 represents driving view, DayNight 0 represents daylight condition, DayNight 1 represents night light condition at night, Notice 0 stands for no notice, Notice 1 stands for voice broadcast, and Notice 2 stands for alarm.

The results of the KS test show that people tend to make random decisions when escaping in the presence of a warning, as demonstrated by the statistically significant deviation from the expected distributions. Without notice, people's decisions are more stable and appear to follow the expected distributions better. People are stable in deciding whether the rain is abnormal across all conditions.

The statistical analysis of ***Tables 2 & 3*** under the height normalization shows that people perceive danger differently in cars and on foot. Furthermore, a comparison of ***Tables 1 & 2*** data indicates that a lower observation height leads to a greater sensitivity to abnormal rainfall. ***Figure 2*** corroborates these findings, depicting that by obtaining a car view, humans possess a heightened sense of danger concerning potential floods compared to a pedestrian view.

Figure 2 indicates that by and large, the average data from the Notice-2, or alarm, condition is less than that of the other conditions. Despite this, the results are insignificant enough to demonstrate a different behaviour between no-notice and alarm. On the other hand, the significant standard deviation of the alarm condition could suffer instability. Nevertheless, humans receive better notifications from the associated alarms than those encountered in voice broadcasts.

Regarding data under different DayNight conditions, there needs to be more evidence that day and night will lead to varying behaviours in detecting all stages.

cross condition p-values:

	abnormal	danger	escape
View0	[0.0358]	[0.0]	[0.0]

Table 1: the p-value of the KS-test for data from different views without height normalisation

cross condition p-values:

	abnormal	danger	escape
View0	[0.7695]	[0.0012]	[0.0]
Notice0	[0.8528, 0.2503]	[0.8528, 0.1614]	[0.9969, 0.1614]
Notice1	[0.0332]	[0.0179]	[0.0332]
DayNight0	[0.6307]	[0.8888]	[0.9659]

Table 2: the p-value of the KS-test for the data distribution with a single independent condition

same condition p-values:

	abnormal	danger	escape
View0	0.212287	0.212287	0.017600
View1	0.982155	0.124694	0.035932
Notice0	0.994161	0.262834	0.139823
Notice1	0.686017	0.067803	0.067803
Notice2	0.139823	0.449037	0.067803
DayNight0	0.212287	0.035932	0.035932
DayNight1	0.706867	0.340066	0.035932

Table 3: the p-value of KS-test for the data distribution within each condition

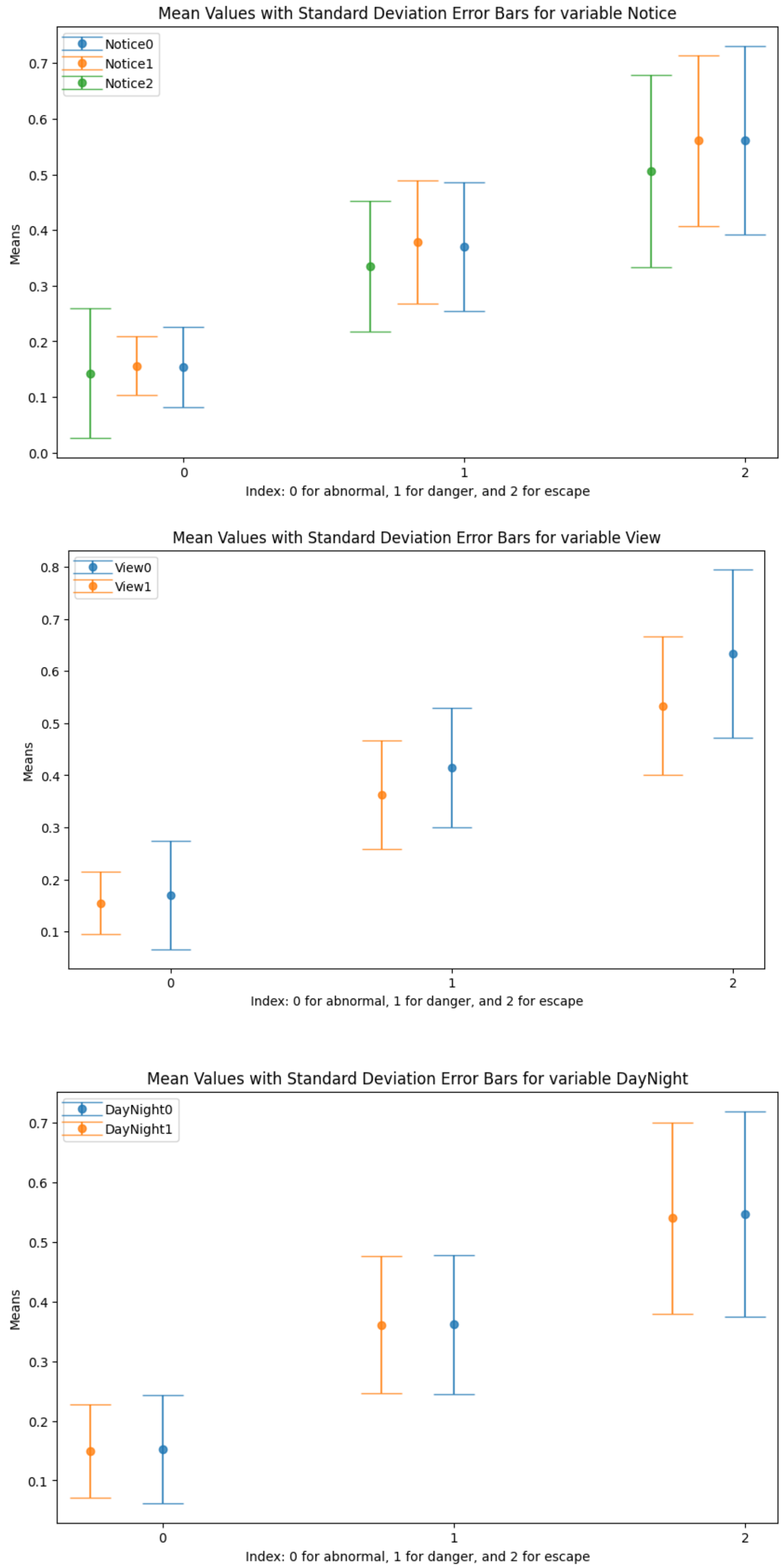

Figure 2: plots of means and standard deviations of data in comparison based on each condition.

6. Policy Implications and Recommendations

The results indicate that fear makes human decisions more random when water levels rise. This thought is further supported by examination of the Notice-1 condition as humans did not expect the water level to surpass expectations that they expected based on the statement "New York City is raining". Compared to the "no-notice" condition, the alarm feature resulted in a lower water level of decision-making at all stages. Thus, it may be prudent to notify people with alarms when elevated or dangerous rainfalls are expected. However, alarms may produce questionable responses during lesser or "abnormal" rains. The ideal course of action would be to not notify during unharmful rainfalls but send warning alarms when greater than dangerous rainfalls are expected.

In light of the findings from various perspectives, proper warning signals must be implemented for pedestrians when flooding occurs since they seem more oblivious to the potential risks than those in vehicles.

In addition, according to water level result from Bernardini et al. (2020):

- 60cm to 70cm of still water can reduce the walking speed by 55%
- 70cm to 120cm of water depth can make it hard to move by feet
- 120cm is the limit for possible evacuation.

As for vehicles, according to result from National Weather Services. (2020):

- 6 inches of water depth is enough to stall most vehicles.
- 1 foot can float a vehicle.
- 2 feet can sweep vehicles away.

The experiment results in Figure 2 indicate a significant delay between the perception of danger and the decision to escape. This is especially true for vehicles, in which subjects would likely not be able to run before water depth rises to 30 cm. This demonstrates that people are often unprepared and inexperienced during flooding, suggesting that caution should be taken when in vehicles or walking on streets, and the decision to low to escape should be made when water depth rises to 30 cm for vehicles or 60 cm when walking on streets. Based on the analysis of the data and experiment, our final policy for aiding citizens during urban flooding is as follows:

1. Based on the water level, deploy the notice: alarm or no notice.
    a) If the water level is expected to be harmful to people's lives, we should deploy the alarm over the street to notify pedestrians first and then deploy the alarm over the car radio.
    b) If the water level is expected to be just an abnormal rain, we will do nothing.
2. We need to organize people well so that people will feel less anxious during flooding:
    a) More publicity about the urban flooding and its repercussion should be conducted, especially on the escape strategies.
    b) Organise flooding drills to get citizens familiar with the escape procedure.
3. VR can be used as an efficient tool for disaster preparedness:
    a) Use a VR environment to conduct immersive drills and let people get used to the flooding safely and economically.
    b) Serve as a testing ground for new disaster preparedness technologies and approaches.

With these policies implemented, citizens will have a much better chance of surviving urban flooding.

7. Conclusions

This project was completed with VR environment development and implemented the functions the experiment design needs. The VR environment is shown to be capable of simulating the flooding process in the city under different scenarios. The experiment tested the rationality of applying VR to disaster preparedness. As a safe, efficient, and easy-to-use tool, the VR environment can provide an immersive disaster experience. It can be applied to various uses, including disaster awareness education, human behavioural analysis, and disaster prevention technology inspection.

In addition, this project initially modelled human behaviour during floods and explored the current disaster awareness of people. This project also documented how different factors affected the evacuation process and tested the efficiency of varying warning methods. Recommendations are made for the policymakers to prevent the loss of life and minimize economic loss in the future. A higher level of disaster preparedness can be expected to be formulated among people with the methodology promoted by this project.

The recommendations for future work are provided as follows:

1. The VR environment needs further development to make the experiment process more automatic and increase realism. Experts should evaluate the environment before being put into real-world use.
2. The analysis made by this project is only possible speculation due to the limited data collected. Volunteers should be recruited to obtain more data to produce a more reliable and generalizable analysis of human behaviour in floods.
3. The VR simulation paradigm can be further applied to disasters, as this project has justified its effectiveness.

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