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Master's Thesis

Earthquake Evacuation Behavior of Foreigners in Osaka Station Based on VR Technology

An Siji

Supervisor: Prof. LAM Chi Yung

Knowledge Science of Advanced Science and Technology
Japan Advanced Institute of Science and Technology
(Master of Knowledge Science)

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Abstract

With the shifts in Japan's economy and society, Japan has attracted more foreign immigrants. With the relaxation of the Japanese government's border policy, the number of foreign tourists in October 2023 in Japan increased by 0.8% compared with that before COVID-19. Moreover, Japan is a country with frequent earthquakes, which presents a greater challenge for foreign residents or tourists with limited capabilities in disaster evacuation compared to native Japanese who have received disaster training since childhood. If we can have a more realistic understanding of the evacuation behavior of foreigners in Japan, it can be very meaningful to improve Japanese disaster response measures and enhance evacuation management capabilities.

So to have a more realistic understanding of the evacuation behavior of foreigners in Japan towards earthquakes, we developed a simulated evacuation VR system using Unreal Engine 4 and PICO 4. The system scene is Osaka Station. We collected behavior sequence datasets of the evacuation behavior of experimenters in real and virtual scenes using different recording methods. We used the Behavior Sequence Analysis method to encode the behavior of each foreign experimenter and analyzed the Levenstein distance between the evacuation behavior sequence in the VR simulation evacuation system and in real-life situations. We also calculated the cosine similarity based on behavior frequency as a vector to explore and analyze the differences in evacuation behavior habits between normal and earthquake situations. In the results section, we analyzed and discussed the differences in each behavior sequence, differences in evacuation behavior data in different environments, the impact of human flow on foreigners' evacuation behavior, route selection, and exit selection preferences.

Keywords: Understanding of the evacuation behavior, Simulated evacuation VR system, Behavior Sequence Analysis

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Finally, I would like to express my gratitude to all my friends at JAIST and colleagues at LAM laboratory. During each seminor, they provided me with some ideas and opinions, which gave me more inspiration to think about my research design. I also hope that this research can make meaningful contributions to Japanese society and academia.

Thank you very much

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Chapter 1

Introduction

With the shifts in the economy and society, the proportion of foreign permanent residents in Japan is gradually increasing. As of the end of 2022, the total number of foreign residents had exceeded 3.07 million [1]. With the significant relaxation of border measures by the Japanese government, as of November 15, 2023, the latest data released by the Japan Government Tourism Bureau shows that the number of tourists entering Japan in October exceeded 2.51 million, a slight increase of 0.8% compared to less than 2.5 million in the same period before COVID-19 in 2019 [2]. Japan is a country with frequent earthquakes, with an average of about 1500 earthquakes occurring each year. The 2011 East Japan Earthquake (also known as the Tohoku Earthquake) was the natural disaster that caused the highest number of losses and deaths in Japan [3].

In order to enhance Japan's earthquake risk management capabilities for foreigners, earthquake simulation evacuation training is an effective means. To achieve this goal, [4] proposed a "FOE+G" model, where "FOE" means the "frequency of occupancy of earthquakes" in Japan and "G" refers to "Gamification", which can make the simulation training process more attractive. Ki-chan's Disaster Evacuation Game[5] is a board game designed to provide a fun and practical way to promote evacuation behavior. However, this desktop game has limitations in replicating complex disaster scenarios. To solve the problem, they proposed a method for players to wear VR headsets to enhance the immersion and adaptability of simulated evacuation training by creating a virtual world similar to their residential area.

VR technology is an application field of computer graphics that allows users to interact with computer-generated images in virtual environments [6]. Using VR technology can improve the 3D visualization and emergency service capabilities of traditional scenes [7]. As an emerging remote interaction technology, VR is a channel that can promote and expand the physical world [8]. Even foreigners who have never been to Japan before can experience the virtual world of Japan through VR technology. Based on the above insights, applying VR technology to the simulation training of earthquake evacuation scenes is an effective solution, and for tourists who have not been to Japan or foreigners who have settled in Japan, it is an effective way to obtain simulation training data at various locations.

For platforms that experience VR content, wearable VR all-in-one devices are now very popular. There are quite a few choices here, such as Facebook's[9] Oculus[10] series all-in-one device, ByteDance's[11] PICO[12] series all-in-one device, and Apple's[13] Vision Pro[14] all-in-one device. They are all head-mounted reality devices with independent processors and support HDMI input simultaneously, with independent computing, input, and output functions. For VR content development platforms, the mainstream choice in the market is based on Unity development[15]. Unity is a cross-platform tool used to create VR content that is compatible with multiple platforms, including PCs, hosts, mobile devices, and web endpoints. In terms of specific functions, Unity currently offers high definition rendering pipelines (HDRP) for VR and universal rendering pipelines (URP) for VR, spatial audio, particle systems, AR Foundation, and mixed and augmented reality workspaces (MARS), among others. Next is the Unreal Engine platform. The Unreal Engine[16] was developed by the renowned gaming company Epic Games[17] and, like Unity, has enormous influence and developer resources worldwide. Unreal Engines are suitable for many industries, such as gaming, movies, architecture, cars and transportation, broadcasting, and VR/AR simulation.

This thesis focuses on discussing the detailed process of developing a VR simulated evacuation system by using Unreal Engine and PICO4, analyzing the behavior of foreigners in the evacuation scene of the virtual Osaka Station by using the Behavior Sequence Analysis method [18], and analyzing their evacuation behavior differences in different scenarios and the behavior changes caused by earthquakes. It can be used as data support for the evacuation planning of Osaka Station to improve the evacuation planning ability of Osaka Station for foreigners.

Chapter 2

Research Background

2.1 Literature Review

For applying VR to earthquake evacuation simulation, [19] used the game engine Unity3D[15] to create a simple VR earthquake simulator prototype, with a focus on earthquake evacuation and participants escaping from inside the building. In the virtual world, they used 3D Unity assets to build a six-story office building model with a rooftop platform in an urban area. This research describes observing the evacuation behavior of participants in a virtual reality earthquake simulator. In a preliminary comparative experiment set up with single and double participants, they found that the VR earthquake simulator provided a real virtual evacuation experience and influenced the evacuation behavior of participants, depending on whether they were accompanied or not. Although they are researchers from Japan who developed a prototype of a VR earthquake simulator and analyzed the behavior of its experimenters, the environment they simulated was not created based on the real Japanese environment, so the analysis of evacuation behavior has little reference significance for real-world evacuation.

[20] developed a virtual evacuation scene using 3D Max and Unity to simulate a typical large-scale shopping mall environment in southern China to explore the impact of route turning angles on evacuation behavior and performance. They verified that route turning angles have a significant impact on human compliance with emergency signals by collecting and analyzing experimental data such as evacuation time, speed, and exit selection. [21] proposed an indoor earthquake evacuation model, simulated pedestrian evacuation in dynamic earthquake scenarios, and constructed an indoor earthquake evacuation system using Unity 2020. Compared with existing models, their model can generate more realistic trajectories. They both analyzed the impact of

various environmental factors on pedestrian evacuation during earthquakes. To explore pedestrian exit selection behavior during evacuation, [22] used 360° videos as materials to create evacuation scenes for VR experiments. They conducted comparative experiments by controlling variables, adding evacuation direction arrows, safety exit information signs, information provided by other pedestrians, and any prompt information to the scene, and studying the impact of different types of information strategies on exit selection. Their limitations lie in the experimenter's inability to freely walk in the virtual environment and the lack of exploration of people's choice of exits when safety exit signs and pedestrian evacuation effects coexist. The above research did not consider the specific impact of pedestrian flow on the experimenter's evacuation behavior, such as whether pedestrian flow affects the experimenter's judgment of safety sign information. And their system direction is too limited, and they have not taken into account the impact of environmental sound and pedestrian flow direction on evacuation behavior.

[23] used 3D Studio Max[24] to simulate a virtual Beijing subway station, conduct evacuation experiments in this immersive virtual environment, and explore the impact of spatial knowledge completeness on the evacuation behavior of subway station passengers. Their research has shown that individuals with spatial completeness knowledge have a strong tendency to evacuate along familiar routes in emergencies, and their evacuation route selections are highly predictable, while participants without spatial knowledge tend to move slower, and their pathfinding decisions are more difficult to predict. It may be the main challenge for subway authorities to manage the evacuation process. They detailed that the completeness of spatial knowledge and the interaction between crowd flow patterns have a significant impact on the evacuation time, distance, and speed of participants. However, how different types of spatial knowledge, including landmark knowledge, procedural knowledge, and survey knowledge, are accumulated in this process and their respective impacts on passenger evacuation behavior are other issues that they have not resolved.

In their subsequent work[25], they continued to use the virtual Beijing subway station mentioned above as an experimental scenario to explore the impact of pedestrian flow on people from different cultures in the evacuation process. Their research found that in highly uncertain situations, people tend to follow the majority of unevenly distributed crowds for evacuation in emergencies involving indoor fires. As the degree of uncertainty during the evacuation process changes, people's attitudes towards following the majority of the crowd may change, and their research indicates that VR-based experiments are an effective method for studying human evacuation behavior in emergencies in buildings. However, because their system route design only has five routes and three DPs, the environment is relatively simple, and the differences in user behavior in finding directions are not too significant. In future work, they also want to evaluate the consistency of pedestrian flow effects in more complex and crowded indoor environments and explore the interaction effects of pedestrian flow with other directional information sources.

[18] simulated an IVR environment based on the actual building of the Auckland Hospital. They used "Behavior Sequence Analysis" to code and classify the actions of the experimenters in the simulated earthquake environment, and then obtained a complete set of earthquake emergency behavior data. Their method demonstrated the richness of behavior information and the dynamic relationship between behaviors, which helps to gain a deeper understanding of the entire behavior process that occurs in earthquake emergencies. However, this study, including the above preliminary studies, did not compare and analyze evacuation behavior in VR environments with real situations. Therefore, it cannot be determined whether the evacuation behavior data obtained in virtual environments has reference value for real situations.

2.2 Contribution and Significance

Inspired by previous research and to strengthen the earthquake evacuation management capability of a certain environment in Japan, the contribution and significance of our research are as follows.

Develop a VR simulation evacuation system that can adapt to the actual situation in Japan, set the virtual scene as a subway environment with voices that correspond to the reality of the situation in Japan, which greatly needs to improve evacuation management capabilities, and collect various evacuation behavior data parameters from the experimenter, thereby providing effective data support for the improvement of the evacuation management system in this environment. These data can also be applied to more complex simulation environments to explore more complex crowd evacuation processes. For example, using the collected real-person evacuation behavior data as a reference template for NPCs in a virtual environment, we can predict the evacuation process in other environments by adjusting the relevant parameters, quantity, and location of NPCs, thereby improving the evacuation management awareness and ability of this complex environment for foreigners.

For an earthquake evacuation simulation environment, our choice is Osaka Station. Using Osaka Station as a simulated evacuation environment has much significance. Firstly, according to data from [26], Osaka ranks third on the list of foreign residents. Foreigners residing in Osaka account for 8.8%

of the total, second only to Tokyo and Nagoya. In 2020, the proportion of international tourists to Osaka was 33.4%, ranking third, only behind Tokyo and Chiba. Kyoto, Nara, and Kobe, which are located in the same western Japan region as Osaka, are all at the top of the international tourist rankings. Considering that Osaka is a transportation hub for western Japan travel, according to Google Maps route recommendations[27], international tourists who target Osaka, Kyoto, Nara, and Kobe as tourist cities will choose to land at Osaka International Airport and pass through Osaka Station, taking the Hankyu train to the corresponding city. Therefore, Osaka Station has a very high utilization rate for international tourists in West Japan. And the Japan Meteorological Agency predicts that Nankai Tough Earthquakes will have a significant impact on where Osaka Station is located in the coming decades[28]. The Osaka Station is a very important research object for both the frequency of use by foreigners and the evacuation management significance for future Nankai Tough Earthquakes.

To explore the impact of human flow on the evacuation behavior of experimenters, we added an NPC human flow model to the virtual experimental environment. To realistically reproduce various human flow models at Osaka Station, we set the human flow model to three different states: talking, walking, and running. Then, by comparing the evacuation behavior of experimenters in normal and earthquake situations, the proportion of experimenters affected by pedestrian flow is explored. A comparison of the impact of pedestrian flow and safety exit information signs on experimenters' pathfinding can be obtained to better understand the patterns of foreigners' crowd evacuation.

We explore the impact of knowledge accumulation that was not analyzed in the above study by comparing the route selections of experimenters in the same environment and different scenarios, as well as the feedback provided by the experimenters. Analyzing the different route memory abilities of experimenters can help us explore or avoid the impact of route memory on their evacuation behavior, thereby verifying the effectiveness and accuracy of the collected evacuation behavior data.

We obtain the proportion of different exit experimenters in the virtual Osaka station environment, which can be used to estimate the carrying capacity of foreign tourists at each exit of the Osaka station under normal and earthquake conditions. This can provide reference data for personalized customization of each exit. For example, during an earthquake, more English-speaking evacuation guides or more English-version evacuation guidance information could be set up at the exit preferred by the foreigners to guide them to the corresponding exit.

Due to the difference between Osaka Station and the simulated real environment in previous studies, such as the Beijing Metro, Osaka Station not only includes various subway and JR entrances and exits but also many shopping malls. We analyze the disparities in the evacuation behavior of participants in two different environments at Osaka Station: an underground shopping mall with limited visibility and a complex multi-story entrance and exit station. It aims to enhance our understanding of how individuals respond during evacuations in different settings. Targeted evacuation management methods can also be provided for the evacuation process in different environments through the differences in evacuation behavior data at Osaka Station.

We process evacuation behavior data based on the BSA (Behavior Sequence Analysis) method[18] and use two similarity analysis methods to analyze evacuation behavior sequences. We also expand the application scope of the BSA (Behavior Sequence Analysis) method to encode each route selection of users. The method of encoding evacuation behavior and route selection can improve the efficiency of analyzing data and also provide a more concise and intuitive understanding of the entire evacuation process of an experimenter through improved state transition diagrams. By verifying the use of these two similarity comparison methods, the similarity of evacuation behavior in both virtual and real environments was explored, demonstrating the effectiveness and limitations of the system under specific conditions and verifying the practical reference significance of the evacuation behavior data. Through the similarity between the evacuation behavior sequences under normal and earthquake conditions in a virtual environment, the differences in evacuation behavior between these two situations are succinctly presented.

Chapter 3

Methodology

3.1 Development Platform

For the development of simulating earthquake evacuation environments, compared to the main-stream Unity [29] development platform used in previous research, Unreal Engine 4 [30] performs well in graphics rendering, with advanced lighting and particle effects, and supports real-time global lighting and high-quality physical simulations. Unreal Engine 4 also provides powerful virtual reality and interactive support, suitable for creating highly immersive VR experiences. We ultimately chose Unreal Engine 4.27.2 as our development platform. For the selection of VR head-mounted devices, considering cost-effectiveness and applicability scenarios, we have selected two products of the same level, Meta Quest2 [31] and Pico 4 [32]. We were considering using a device that could better present our earthquake evacuation simulation system to users. Pico 4 has relatively higher hardware parameters, such as resolution and field of view. Moreover, it features a foldable optical battery with a rear design, making it more comfortable to wear [33]. Therefore, for a VR earthquake simulation evacuation experiment, considering the long duration and the effect of image jitter on the user's adaptive experience, we selected Pico 4 as our development equipment.

3.2 Scene Modeling

For generating internal scenes of Osaka Station, we consider using Google's Street View Map [34] and Osaka Station's 2D plane diagram [35] as parameter information for reconstruction on the Unreal Engine. Due to copyright concerns, we solely focus on reproducing the general internal layout of Osaka Station. To provide accurate scene details, such as store and platform names, we utilize copyrighted items from the Unreal Mall as replacements. As shown in Figure 3.1 and Figure 3.2, these are simulation effects of some subway scenes.

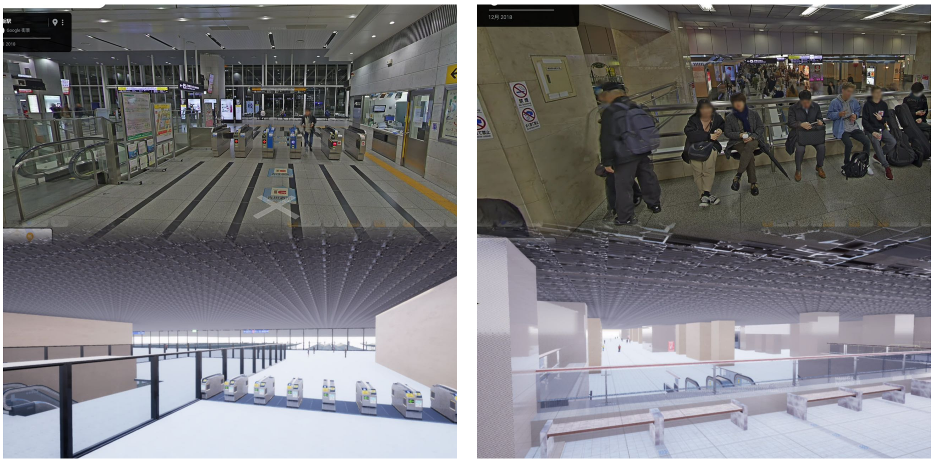

Figure 3.1: Simulation Effects of Subway Scenes

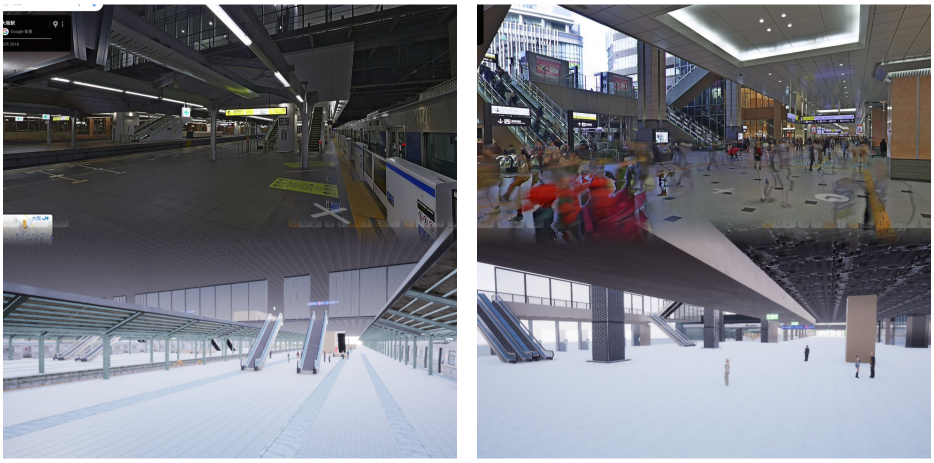

Figure 3.2: Simulation Effects of Subway Scenes 2

3.3 Immersive Earthquake Effects

For earthquake scenes, we used the method of binding camera shake effects [36] to user cameras to present the effects. Based on some relevant real parameters of common magnitude 4 earthquakes, magnitude 6 earthquakes, and magnitude 8 earthquakes [37], we adjusted camera shake parameters such as oscillation frequency, frame duration of each oscillation effect, and set attenuation effects to divide the camera oscillation effect into three modes. To restore the true evacuation environment of Osaka Station as accurately as possible, we went to Osaka Station to collect some real sound information, such as the sound of human flow and some voice broadcasts. Then, we collected some real online noise of Japanese earthquake evacuation and related earthquake alarm sounds, and we made corresponding noise reduction treatments on all sound samples to avoid privacy infringement. We added these sounds to the animation frames triggered by the relevant blueprint events. For example, once an earthquake is triggered, the corresponding sound samples are naturally replaced to present the subway evacuation scene to the user as realistically as possible, making the user more immersed in this evacuation scene and obtaining more realistic user behavior. These triggering events were written into the level blueprint, and the specific execution process of the level blueprint is shown in Figure 3.3.

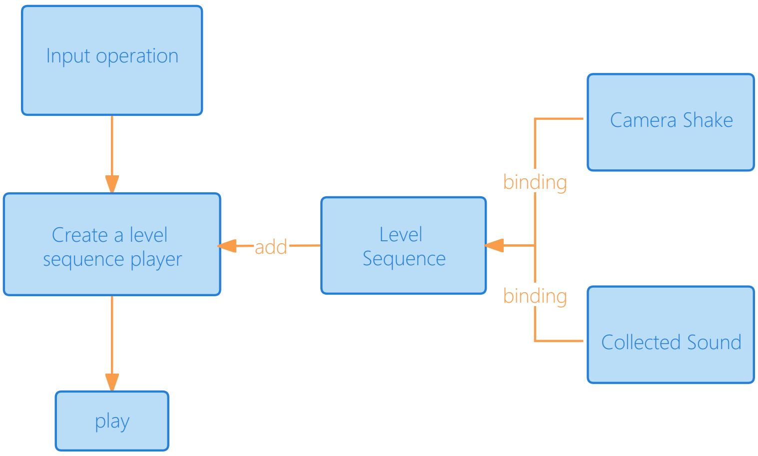

Figure 3.3: Level Blueprint Flow Chart

3.4 Subway Pedestrian Flow Model

For the pedestrian flow model in the subway scene, we have set up five types of pedestrian flows heading towards different exits. These five types of pedestrian flow destinations are North Central Gate, South Central Gate, Sakurabashi Gate, Midosuji North Gate, and Midosuji South Gate [35]. For these five types of people, we created corresponding mixed-space 1D, animation blueprints, and character blueprints. Mixed Space 1D is mainly used to define the animation parameters of characters in different states. Here, we used the character's movement speed as the boundary value for animation changes. For example, when the movement speed is greater than 100 units, a running animation is executed; when the movement speed is less than 100 units, a walking animation is executed, and when it reaches 0 units, an animation of staying in place and looking around is executed. The animation blueprint is mainly used to launch the corresponding mixed animation player to execute the corresponding animation posture of the character, the character blueprint is mainly used to set the skeleton mesh of characters and simulate characters in the scene by adding different character models. And with adding corresponding event charts for characters into the character blueprint, such as adding their target movement positions and some triggering events to execute corresponding character behaviors. Then we added the NavMeshBoundsVolume-Control Model to the scene to automatically navigate three hundred people to their destination [38]. The initial state of the crowd in the scene is random, and they will be automatically assigned a random speed parameter to represent their current state when the level starts. When an earthquake event is triggered in the level blueprint, their speed will randomly increase to a speed greater than 150 units, and they will execute a running animation and then run toward their respective destinations. Due to the limitations of the 11th Gen Intel (R) Core (TM) i7-11370H @ 3.30GHz processor configuration and NVIDIA GeForce RTX 3070 Laptop GPU graphics card configuration, we have only set up 300 random flow characters at different locations in the scene to avoid system overload. As shown in Figure 3.4, Figure 3.5 and Figure 3.6, these are different character states in different scene states, corresponding to behaviors such as talking, walking, and running.

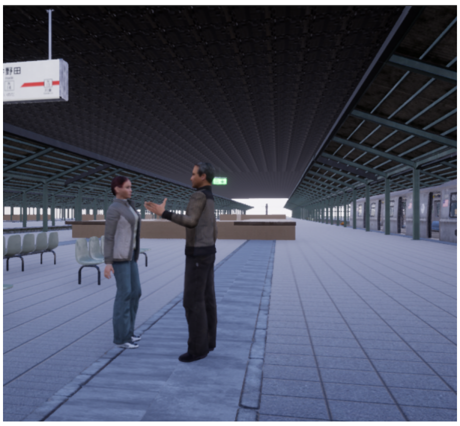

Figure 3.4: NPC talking state

Figure 3.5: NPC walking state

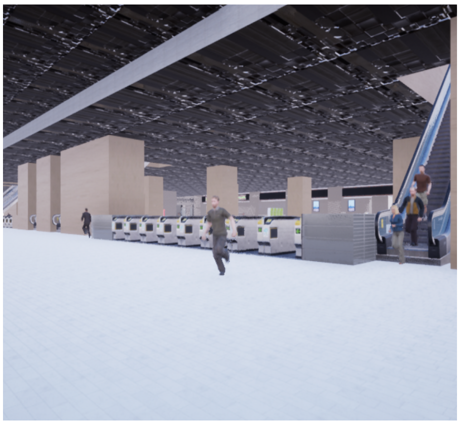

Figure 3.6: NPC runing state

3.5 User Behavior Mapping

For the mapping of user evacuation behavior in virtual scenes, we mapped the button behavior of users operating Pico [32] controllers to the motion behavior of objects in the virtual scene. For example, the sliding behavior of the left-hand joystick is mapped to the movement of the user's body in various directions in the virtual scene, while the movement of the right-hand joystick is mapped to the movement of the user's physical position in the virtual scene. There are two schemes for mapping and configuring controller behavior in Unreal Engine. One solution is to directly enable the relevant plugins of PICO and automatically add controller event behavior in the project settings. Although this solution is very convenient, when running the simulation system through the PICO 4 stream virtual engine, there will be more detection of the two built-in controller screens in PICO, which will affect the visual effect. Our solution is to close all PICO plugins, enable relevant plugins for Oculus Quest2 [31], and then refer to the official documentation for Oculus Quest2 to add binding Quest2 handle mapping events. Surprisingly, the controller of PICO 4 can directly map user behavior through Oculus Quest2-related binding events, and the detection controller screen of the PICO 4 screen will disappear. This is an effective way to solve the problem of screen detection controllers encountered in development using PICO 4+ Unreal Engine 4. As shown in Figure 3.7, this is an event chart related to the change in first-person perspective position corresponding to user movement input in the scene.

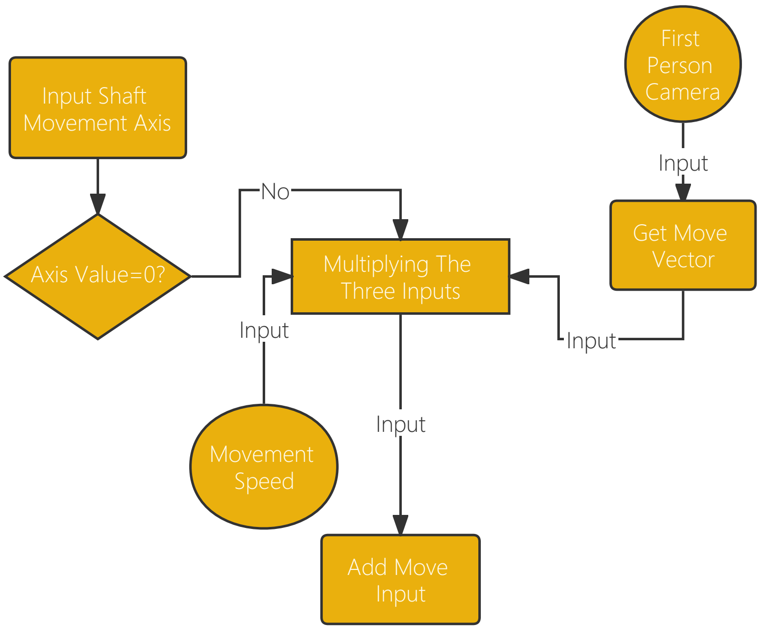

Figure 3.7: Movement Input Mapping

3.6 Application Testing

For practical application performance testing, one way is to install Android Studio and the corresponding Pico Unreal Integration SDK [39], configure the relevant parameters of the Unreal Engine, and finally package the project as an Android executable project to download and run on Pico4.

When packaging the scene project, there will be a configuration issue with rungradle.bat. Due to the lack of timely updates to Pico's official documentation, it is currently difficult to find a solution to this problem in the development platform community and on the internet. Our solution is to load multiple versions of the SDK and NDK in Android Studio [40], and then download JDK1.8.0.77 again from the JAVA official website [41]. By configuring the JRE version into the Unreal Engine, this issue can be resolved. For the binding of the project to Pico 4 devices, it is necessary to load the Pico 4 plugin and automatically load the default version of Pico controller events or modify the corresponding controller events after dragging the Pico VR pawn into the scene. After binding various user events to the blueprint object, the corresponding interaction mapping of the project to Pico 4 devices can be completed after packaging.

For application testing, there is another simpler approach here. Due to differences in the environment variables required for different development tools, especially for developers using multiple programming languages, some versions of environment variable configurations may not be compatible with multiple software. In order to solve the problem of other development tools being incompatible with different versions of JRE and Android Studio, as well as the problem of the relevant configuration environment being unable to parse files during the packaging process, application testing can also be carried out by directly connecting VR headset devices with the Unreal Engine. Through this method, when it is necessary to constantly modify or add application content during application testing, it can save time in migrating packaging resources and avoid consuming too much storage space with duplicate packaging resources.

Chapter 4

Experiment

4.1 Participants

We searched for six experimenters (3 males and 3 females) who have complete spatial knowledge of the Osaka Station. They are international students from the Ibaraki area in northern Osaka Prefecture. To save on house rent, they all live in the Shin Kitano area of Osaka City. They usually take the Sanyo Main Line to transfer from Osaka Station to school (3-6 times a week). They are very familiar with the specific commuting routes of Osaka Station, so they have relatively "complete spatial knowledge" [23] of Osaka Station.

Then we searched for 14 international students (7 males and 7 females) from the Ishikawa Prefecture area to do the next experiment. They have just experienced the 2024 Noto Peninsula Earthquake [42] in the Nomi area, about 100 kilometers away from the Noto area in Ishikawa Prefecture. Recruiting them for a simulated evacuation experiment can improve their psychological resilience when dealing with possible aftershocks caused by the Noto Peninsula Earthquake and enhance their ability to adapt to visual oscillations caused by earthquakes. At first, they were asked to do a questionnaire to test their knowledge of the spatial completeness of Osaka Station. Through the questionnaire, we found that most of them have visited the Osaka Station no more than three times a year, so it can be understood that they do not have complete spatial knowledge of the Osaka Station.

4.2 Experiment design

To explore and analyze whether the completeness of spatial knowledge for Osaka Station will affect evacuation behavior, we set up two rounds of experiments. Participants in one round have spatial knowledge completeness for Osaka Station, while participants in the other round do not have spatial knowledge completeness for Osaka Station. For the first round of experiments, we have decided to use the Repeated Measures Design experimental method [43]. Here, the same experimenter is required to conduct four sets of experiments to find exits, named Task 1 - Task 4. Task 1 and Task 4 are searching for exits in the real environment, while Task 3 and Task 4 are searching for exits in the virtual environment. The initial position of Task 1 is the same as the virtual initial position of Task 3, while the initial position of Task 2 is the same as the virtual initial position of Task 4. The first initial position is a location that they must pass through in their real life, that is, the exit for transferring trains at Osaka Station every time they return from school. Another place they don't often pass by is the EKI MARCHE OSAKA food and shopping plaza on the first floor of Osaka Station. The environment here is relatively narrower, with a narrow view and no particularly large exit signs to guide the experimenters in finding exits. Therefore, by comparing with the previous initial location, we can also analyze the differences in people's evacuation behavior at the underground shopping mall and entrance/exit of Osaka Station. Finally, by comparing the differences in evacuation behavior between real and virtual environments, we explored and analyzed the systematic errors of virtual environments to verify the accuracy and effectiveness of virtual evacuation systems in analyzing evacuation behavior. After doing that, we also obtained reliable parameters for system optimization, such as the walking speed of people in virtual environments relative to the entire space.

For the second round of experiments, we also used the experimental method of Repeated Measures Design. Here, each experimenter will be required to conduct six sets of experiments to find exits, named Task 5 - Task 10. Task 5 to Task 7 are conducted in a virtual environment without earthquakes, while Task 8 to Task 10 are conducted in a virtual environment with earthquakes. The initial positions of Task 5 and Task 8 are the same, Task 6 and Task 9 are the same, and Task 7 and Task 10 are the same. We have set the initial positions of Task 5 and Task 8 at the JR platform on the next floor below the JR central exit. From here, the exit signs for North Central Gate, South Central Gate, and Sakurabashi Gate are located Within the same field of view, so all three exits may become the intended exit for the experimenter, the specific location here was at platforms 5 and 6 of JR Osaka Station. By setting the initial position in this way, we can obtain the user's preferences for these three exits in both normal and earthquake states. The initial positions of Task 6 and Task 9 were located at the EKI MARCHE OSAKA food and shopping plaza on the first floor of Osaka Station. Similar to the previous reasons, the differences in evacuation behavior of people at the underground shopping mall and entrance/exit of Osaka Station can also be analyzed by comparing with the previous initial positions. The initial positions of Task 7 and Task 10 were set at the locations where the experimenters will have the opportunity to pass through in real life. Here, the initial location of Task 7 and Task 10 was at JR platform 11, which is heading towards Kanazawa by taking the Thunderbird Line. The main reason for setting this location is that if the participants who do the experiments need to take JR back to school from Osaka Station, this is the place they must pass by and wait for the train. They are the real users in this evacuation environment, so starting from here to conduct simulated evacuation experiments can more closely reflect the crowd evacuation situation in this real environment.

4.3 Experiment Process

As shown in Figure 4.1, the first round of experimenters with complete spatial knowledge at Osaka Station first wore helmets equipped with motion cameras, which would record the entire process of searching for exits at the Osaka station. Due to the inability to swipe the ticket gates in Japan both upon entry and exit at the same station, we instructed participants in the initial round of Task 1 trials to commence their journey from school and travel via the Sanyo Main Line to Osaka Station. After arriving at the designated location, they activated a motion camera to record the behavior trajectory of searching for the exit. The Task 2 experiments required them to enter the EKI MARCHE OSAKA entrance near JR Osaka Mitsukoshi Isetan and search for a safe exit. Then Task 3 and Task 4 required them to wear PICO 4 for the experiment, as shown in Figure 4.2. Before the official start of the experiment, they should undergo adaptive training on moving in a VR environment in an open environment. We told them how to use the VR controller to control their movement in the VR scene. They would start the experiment when they have fully adapted to the operation method, avoiding the influence of unfamiliarity with the device operation method on the final experimental results. The initial position of the Task 3 experiment corresponds to the initial position of the Task 1 experiment, while the initial position of the Task 4 experiment corresponds to the initial position of the Task 2 experiment.

Then the second round of experimenters without complete spatial knowledge wore PICO 4 and participated in six groups of experiments, from Task 5 to Task 10. Before starting the experiment, they would wear sanitary masks for the VR experience to ensure the hygiene of the experimenter's face and

Figure 4.1: Actual Evacuation Scene and Recorded Footage

VR equipment. They were also required to disinfect their fingers in advance to ensure the hygiene of the VR handle. Before the formal start of the experiment, they also need to conduct adaptive training on moving in a VR environment in an open scene, just like the previous round of experimenters, to avoid the influence of unfamiliarity with device operation methods on the final experimental results. Due to the long duration of their experiment wearing VR glasses, we divided the experiment into two rounds and arranged for them to rest for about ten minutes. If any 3D dizziness or other uncomfortable symptoms occur during the experiment, they can stop the experiment.

Figure 4.2: Virtual Evacuation Scene and Recorded Footage

Chapter 5

Results

In order to present the evacuation behavior of the experimenters in different environments in two rounds of experiments more concisely, we replaced each evacuation behavior with the encoding of a-i, as shown in 5.1. This is the behavior analysis comparison table we created. For people's evacuation behavior, we regard the default state as "move" because the main task of the experimenters is to move in a simulated evacuation environment. We do not encode "move" into the behavior sequence because there will be a high frequency of "move" behavior between each sequence encoding transformation, which will result in a very high similarity between each behavior sequence, making it difficult to analyze the differences between behavior sequences.

Behavior Coding	Evacuation Behavior
a	Accurately follow the safety exit signs for movement
b	Did not move according to the instructions
c	Looking around for directions or safety exit signs
d	Remain where one is
e	Follow the flow of people (opposite to the exit sign)
f	Follow the flow of people (in the same direction as the exit sign)
g	Go downstairs
h	Turn around and walk back
i	Go upstairs

Table 5.1: Behavior Code and Evacuation Behavior Association Table

5.1 State Transition Diagram

UML sequence diagrams have higher visualization and readability, while automaton models have stricter definitions and better verifiability. Combining the complementary advantages of the two models, [44] proposed a behavior description and formal validation method called formal sequences. It integrates the advantages of extended UML sequence diagrams and automata models and can clearly express the transition process of behavior sequences. Here, we use numbers to represent the transition order of each state. By encoding the various behaviors of the experimenter, we can express the behavior transition process of the experimenter in a specific scenario in the form of a state transition diagram. In this way, we can more intuitively understand people's evacuation behavior in a specific scenario. As shown in Figure 5.1, this is the state transition diagram of experimenter 11 in Task 8.

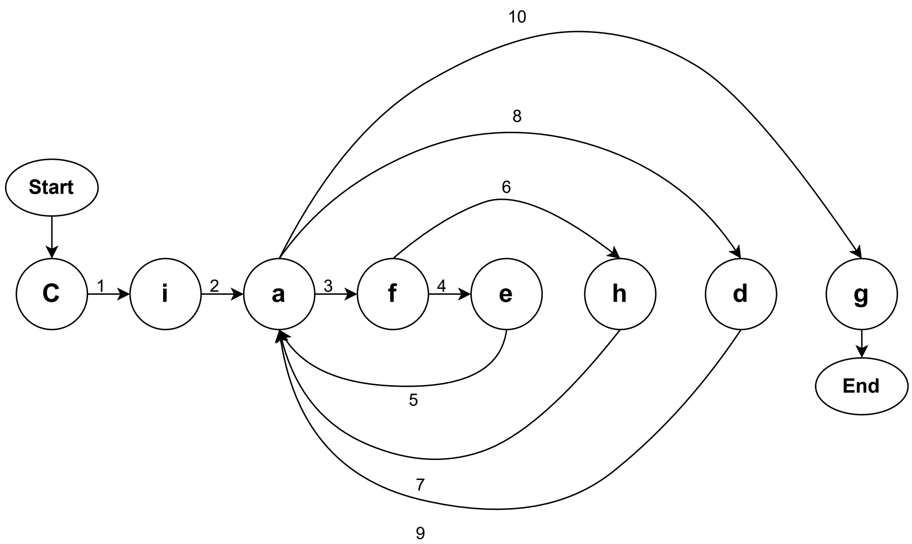

Figure 5.1: State Transition Diagram

5.2 Behavior Sequence Similarity

By using the state transition diagram in the above figure, we can transform the set of behaviors of the experimenter in a specific scenario into a sequence of behaviors. For example, according to the behavior transition diagram in Figure 5.1, the behavior of the experimenter in a specific scenario can be described as a sequence of behaviors such as "ciafeahadagag". So in different scenarios, the comparison of the experimenter's behavior data will be transformed into a comparison between sequences. Here, we used Levenshtein Distance [45] to represent the differences between sequences, that is, the differences in evacuation behavior in different scenarios. In order to better express the similarity of the experimenter's behavior in both real and virtual scenes, we used Leven-Similarity to represent their differences based on Levenshtein distance between two sequences, the calculation rules are shown in 5.1.

Then we used the frequency of each character element as a vector feature, that is, the frequency of each behavior as a feature of the behavior sequence, which converted each behavior sequence into different behavior vectors, and finally, we calculated the cosine-similarity [46] to obtain the similarity results of evacuation behavior in different scenarios. The calculated similarity can reflect the similarity of their behavior habits and preferences in real and virtual environments. This method does not consider the order of behavior sequence.

As shown in Table 5.2, it shows the similarity between the behavior sequence of the experimenter in the actual environment and the virtual environment, with the initial position at the platform where the experimenter commutes daily. As shown in Table 5.3, shows the similarity of the behavior sequence of the experimenters in the actual and virtual environments at the initial position of EKI MARCHE OSAKA entrance near JR Osaka Mitsukoshi Isetan.

$$\text{Leven-Similarity} = 1 - \frac{\text{Levenshtein Distance}}{\text{Maximum Possible Distance}} \tag{5.1}$$

- Levenshtein Distance: Minimum number of single-character edits required to change.
- Maximum Possible Distance: Length of the longer sequence in the compared sequences.

Experimenter	Leven-Similarity	Cosine-Similarity
Participant 1	0.778	0.915
Participant 2	0.778	0.969
Participant 3	0.833	0.961
Participant 4	0.857	0.961
Participant 5	0.778	0.948
Participant 6	0.727	0.936
Average	0.792	0.948

Table 5.2: Similarity of Evacuation Behavior between Task 1 and Task 3

Experimenter	Leven-Similarity	Cosine-Similarity
Participant 1	0.714	0.977
Participant 2	0.692	0.988
Participant 3	0.625	0.905
Participant 4	0.625	0.899
Participant 5	0.667	0.932
Participant 6	0.625	0.978
Average	0.658	0.946

Table 5.3: Similarity of Evacuation Behavior between Task 2 and Task 4

From Table 5.2 and Table 5.3, we can see that the average cosine similarity of evacuation behavior habits among the experimenters in both real and virtual environments is almost 95%. It can also be seen that the experimenters have very similar behavior habits regarding finding exits in both real and virtual environments.

Next, we can know from another result in Table 5.2 that when the experimenters are in a fully familiar virtual environment (i.e., the initial position in the virtual environment is the same as their daily position when exiting the subway at Osaka Station), the average Leven-Similarity, which represent their behavioral similarity, is 0.792. This can prove that this system, without considering the experimenter's unfamiliarity with the internal environment of Osaka Station (excluding the influence of behavioral differences caused by the experimenter's thinking direction and pathfinding), can nearly 80% restore the evacuation behavior of people with spatial completeness knowledge of Osaka Station in the real environment.

Next, we can know from Table 5.3 that the average values of Leven-Similarity have decreased compared to Table 5.3. The main parameter that changes compared to the previous group of data is the initial position of evacuation. Their initial positions in both virtual and real environments are set at EKI MARCHE OSAKA, where they have almost no visiting experience. According to our collected data, they missed or did not follow the safety exit sign information more times in the real environment than in the virtual environment, and stopped in place more times in the virtual environment than in the real environment, resulting in a larger difference in their behavior sequence. We have received some feedback from the experimenters here, as there are more people in the real environment, the store environment is more complex, and many types of products and different pedestrians distract their attention, so they may missed some safety exit information. Due to psychological influence, they did not want to stop in crowded places in the real environment, afraid of obstructing pedestrians who walk normally in narrow spaces, which leads to them hardly staying in one place.

Experimenter	Leven-Similarity	Cosine-Similarity
Participant 7	0.471	0.950
Participant 8	0.438	0.895
Participant 9	0.5	0.866
Participant 10	0.462	0.836
Participant 12	0.588	0.951
Participant 13	0.211	0.944
Participant 14	0.450	0.940
Participant 15	0.421	0.975
Participant 16	0.385	0.963
Participant 17	0.363	0.774
Participant 18	0.231	0.567
Participant 19	0.462	0.842
Participant 20	0.333	0.753
Average	0.409	0.866

Table 5.4: Similarity of Evacuation Behavior between Task 5 and Task 8

Due to experimenter 11 experiencing 3D dizziness and discomfort during the experiment, and her data being greatly affected by physical discomfort, there were too many pauses displayed in the evacuation dataset, which may lead to inaccurate data processing. Therefore, our data analysis did not consider Participant 11's data. From the data in Table 5.4 and Table 5.6, we can know that when the experimenter's initial position in the virtual environment used in this experiment was placed on the subway platform, the Leven-Similarity (the similarity of evacuation behavior sequences) between normal and earthquake situations are 0.409 and 0.415, and the cosine similarity (i.e. the similarity of evacuation behavior habits using various evacuation behavior frequencies as vectors) are 0.866 and 0.828. That is to say when an earthquake occurs, people's evacuation behavior patterns (considering the order of various behaviors) may only be about 40% the same as the scene with no earthquake, and people's evacuation behavior habits under normal circumstances are about 83%-87% the same as those under earthquake conditions.

Compared to Table 5.5, this experiment's initial location is in the relatively enclosed underground shopping mall of Osaka Station, which has only one floor. Its Leven-Similarity reaches 0.512, while Cosine Similarity reaches

Experimenter	Leven-Similarity	Cosine-Similarity
Participant 7	0.417	0.857
Participant 8	0.412	0.911
Participant 9	0.625	0.938
Participant 10	0.5	0.964
Participant 12	0.625	0.906
Participant 13	0.571	0.973
Participant 14	0.467	0.887
Participant 15	0.636	0.953
Participant 16	0.714	0.885
Participant 17	0.294	0.941
Participant 18	0.454	0.849
Participant 19	0.667	0.983
Participant 20	0.273	0.927
Average	0.512	0.921

Table 5.5: Similarity of Evacuation Behavior between Task 6 and Task 9

0.921. From this result, we can conclude that in the environment of the Osaka Station underground shopping mall, which has a relatively narrow field of view and limited space, when an earthquake occurs, the evacuation behavior patterns of the experimenters (considering the order of various behaviors) are more than 50% the same as the normal situation without an earthquake. People's evacuation behavior preferences under normal circumstances are approximately 92% similar to those under earthquake conditions.

According to the feedback from experimenters and careful analysis of the experimental data, we found that in the virtual underground shopping mall environment (EKI MARCHE OSAKA), most of the experimenters did not engage in any behavior of going upstairs or downstairs in Tasks 6 and 9. Moreover, the underground shopping mall did not require people to make the choice of going upstairs or downstairs like in a subway platform environment, the experimenters were more focused on finding safety exit signs. From the collected data, we can also know that in the evacuation behavior sequences of Task 6 and Task 9, there are many fewer behaviors that miss or do not comply with the safety exit indicator information, so there are fewer elements "b" in the two evacuation behavior sequences. These reasons all lead to an increase in the Leven-Similarity compared with other tables.

Experimenter	Leven-Similarity	Cosine-Similarity
Participant 7	0.6	0.949
Participant 8	0.25	0.756
Participant 9	0.267	0.810
Participant 10	0.714	0.945
Participant 12	0.4	0.787
Participant 13	0.571	0.781
Participant 14	0.368	0.671
Participant 15	0.276	0.770
Participant 16	0.267	0.904
Participant 17	0.333	0.804
Participant 18	0.357	0.819
Participant 19	0.588	0.935
Participant 20	0.407	0.832
Average	0.415	0.828

Table 5.6: Similarity of Evacuation Behavior between Task 7 and Task 10

5.3 Specific Evacuation Behavior Differences

As shown in Figure 5.2, Figure 5.3, and Figure 5.4, these are comparisons of specific behavior data for each scenario. The vertical axis represents the average number of occurrences of behavior, while the horizontal axis represents the behaviors of each group(Letters represent behavior codes, and numbers represent experimental group numbers). From the three graphs, we can know that compared to the normal scenario, the number of times the experimenters correctly evacuated according to the safety exit sign information in the earthquake scenario decreased, the number of times they missed the safety exit sign information or saw the safety exit sign information but did not move according to the instructions increased, and the number of times they looked around to find direction or safety exit signs also decreased, the number of times to remain stationary decreased, while the number of times to turnaround and move increased.

5.4 The Impact of Human Flow on Evacuation Behavior

From Figures 5.5, 5.6, and 5.7, we can know that in the scene without any earthquake, only one person was affected by the flow of people in the scene of

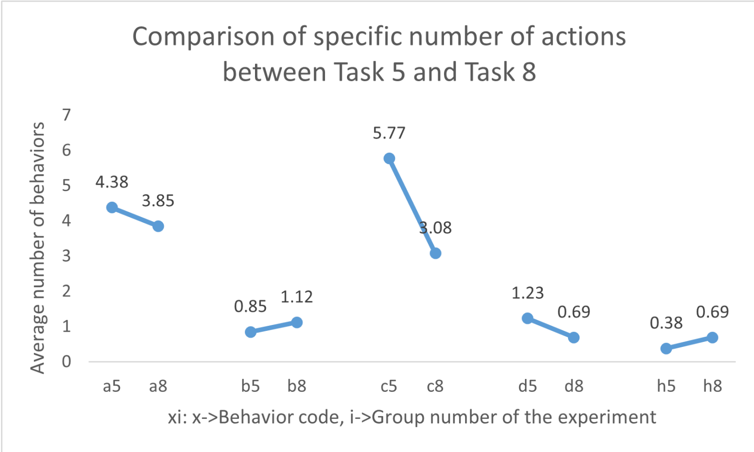

Figure 5.2: Comparison of a specific number of actions between Task 5 and Task 8

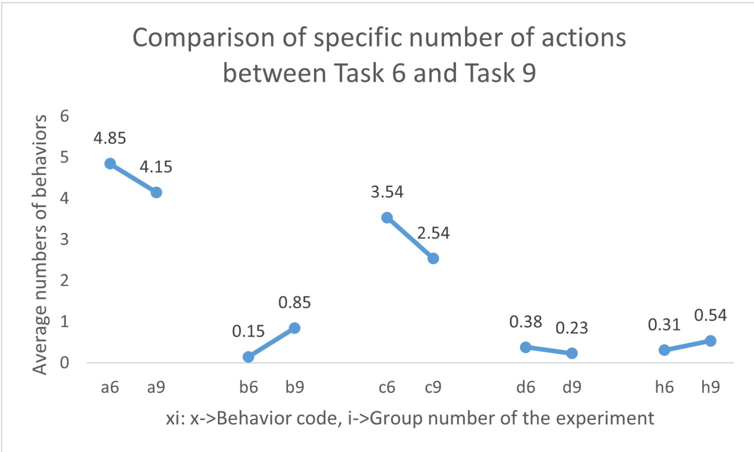

Figure 5.3: Comparison of a specific number of actions between Task 6 and Task 9

Task 5 and followed the flow to find the exit. Therefore, we know that in the scene without any earthquake, the vast majority of people will not be affected by the flow of people to find the exit. In the earthquake scenario of Task 8, we can see from the first pie chart that nearly 85% of people are affected by the flow of people. Among them, 38.46% of people followed the flow of people running in the direction indicated by the safety exit information for evacuation, while 46.15% of people followed the flow of people running in the direction not indicated by the safety exit information for evacuation. This means that even if they see the direction indicated by the safety exit sign,

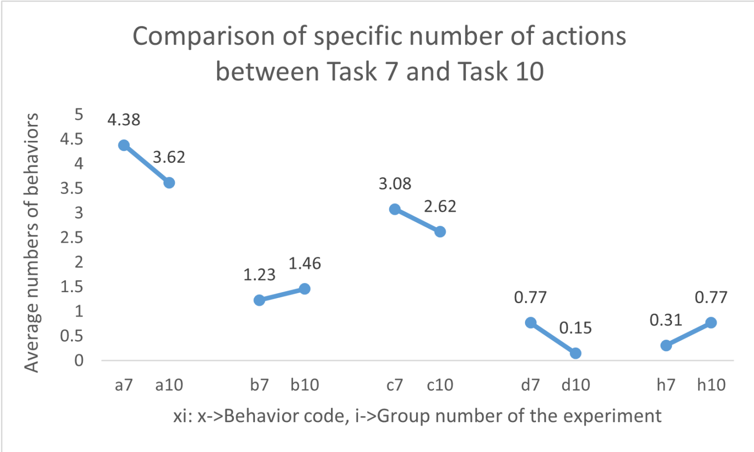

Figure 5.4: Comparison of a specific number of actions between Task 7 and Task 10

they did not make independent decisions and followed the direction in which the safety exit information is indicated. They preferred to trust the direction of the flow of people who were running.

In the earthquake scenario of Task 9, from the second pie chart, we know that in underground shopping malls with relatively small field of view and narrow space, 61.54% of people were affected by pedestrian flow, of which 38.46% followed the direction indicated by the safety exit information for evacuation, and 23.08% did not follow the direction indicated by the safety exit information for evacuation. We have obtained the reason for the change in evacuation behavior data from feedback from some experimenters, they said that the spatial structure of underground shopping malls is relatively simple, without elevators and stairs, they were more likely to focus on safety exit signs in this environment, rather than first considering which floor they were on. From the data we collected, we also found that in underground shopping environments such as Task 6 and Task 9, only one person engaged in the behavior of going upstairs and downstairs. So we can find another possibility that in environments with relatively simple spatial structures, especially those with only one floor, people's evacuation behavior will be less affected by human flow compared to environments with complex spaces and multiple floors. Fewer people will follow the flow of people who do not follow the direction indicated by the safety exit information for evacuation in the relatively simple spatial environments.

In the earthquake scenario of Task 10, we can see from the third pie chart that nearly 70% of people were affected by the flow of people, of which 38.46% would follow the flow of people running in the direction indicated by the safety exit information for evacuation, and 30.77% would follow the flow of people running in the direction not indicated by the safety exit information for evacuation. Compared to the data on the impact of human flow in Task 9, the increase in the number of people doing the "e" behavior also confirmed the conclusion mentioned above that in environments with relatively simple spatial structures during earthquakes, people's evacuation behavior is less affected by human flow.

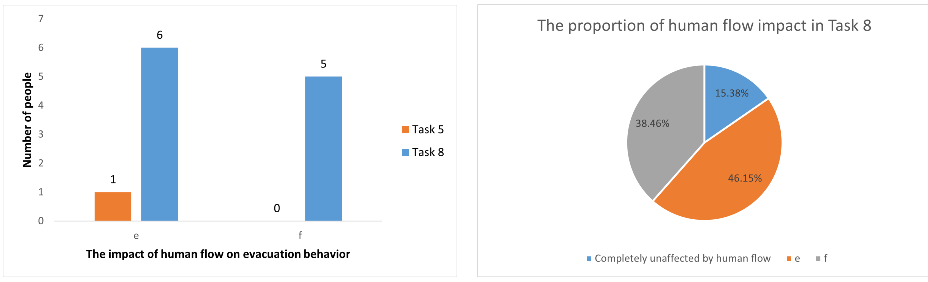

Figure 5.5: Comparison of Human Flow Impact between Task 5 and Task 8

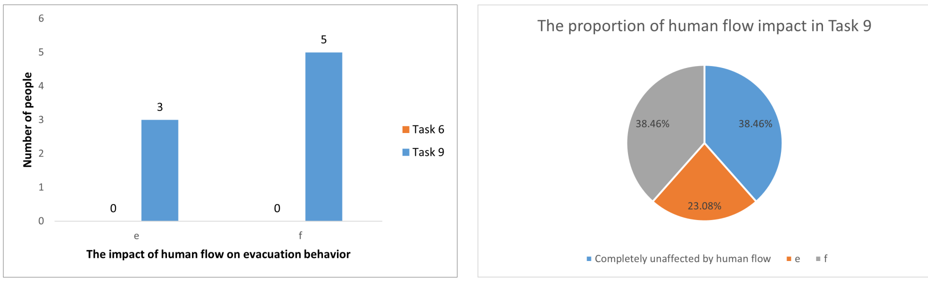

Figure 5.6: Comparison of Human Flow Impact between Task 6 and Task 9

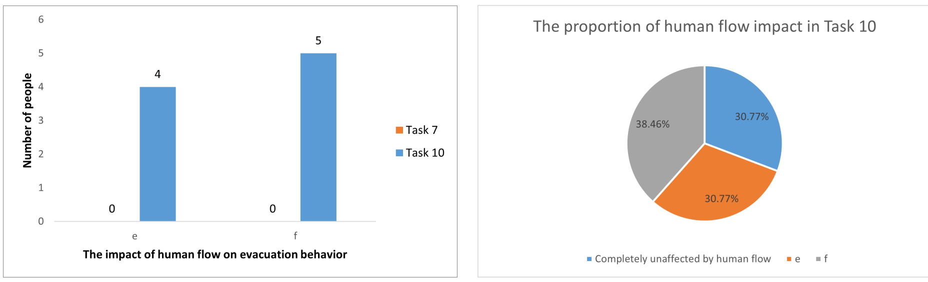

Figure 5.7: Comparison of Human Flow Impact between Task 7 and Task 10

5.5 Selection of Route

Regarding each route selection, we numbered the different passable paths of the experimenter, as shown in Figure 5.8 and Figure5.9. These are partial route numbers. When the experimenters selected one of these passable paths, we recorded their selection and then connected all the selections to form their route selection sequence, such as (a1, b1, c1, d1). Then we compared the path sequences of Task 5 and Task 8, Task 6 and Task 9, and Task 7 and Task 10 for each experimenter to find individuals who had chosen the same path twice. As shown in Table 5.7, for the experiment with initial positions at platforms 5 and 6, the two route selections of experimenter 7 and experimenter 9 were completely identical. For the experiment with initial positions at EKI MARCHE OSAKA, the two route selections of experimenter 9, experimenter 18, and experimenter 19 were completely identical. For the experiment with initial positions at platform 11, the two route selections of experimenter 9, experimenter 18, and experimenter 19 were completely identical. We can also find that experimenter 9 always followed the same route as the previous one to exit, regardless of where the initial position was. After feedback from them, experimenters 7, 18, and 19 stated that they did not feel like they remembered the route and chose the same route as before. They only strictly relied on the safety exit signs to choose the evacuation route. We found from their evacuation behavior sequence that their behavior of "b" is less frequent, and when this behavior occurs, they all pass through the same safety exit sign. From the feedback of experimenter 9, we learned that she is a person with a strong sense of spatial direction. She stated that she is sensitive to the spatial environment and has a deep memory of the routes in a short period. So from this, we can find that in such a complex environment at Osaka Station, the evacuation behavior of the experimenter is very little affected by the memory of the route. Most people cannot remember their previous routes after going through a pathfinding process at once.

	Task5-Task8	Task6-Task9	Task7-Task10
	Participant 7		
	Participant 9	Participant 9	Participant 9
		Participant 18	Participant 18
		Participant 19	Participant 19
Ratio to all experimenters	15.4%	23.1%	23.1%

Table 5.7: Statistical table with the same route selected

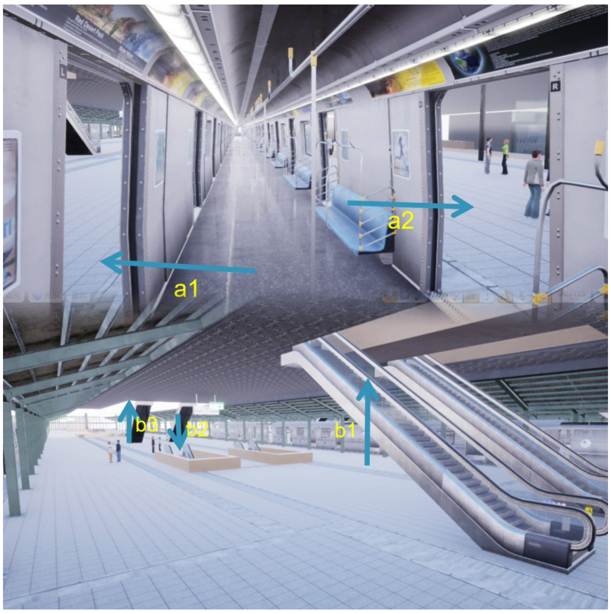

Figure 5.8: Partial route selection number

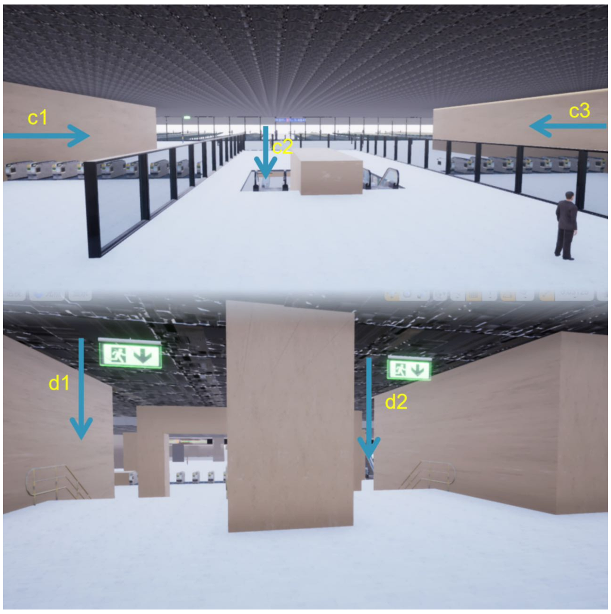

Figure 5.9: Partial route selection number

5.6 Selection of Exits

As shown in Figure 5.10, Figure 5.11, and Figure 5.12, these are the selections made by the experimenters for each exit in various scenarios. From

Figure 5.10, we can see that 53.85% of people will evacuate to the North Central gate in both normal and earthquake scenarios. This is the main exit selection for people at platforms 5 and 6 of JR Osaka Station, and there is also a certain possibility for the other four exit selections.

As shown in Figure 5.11, we can see that under normal circumstances, 92.31% of people chose to evacuate to the Sakurabashi gate, while 7.69% of people chose to evacuate to the North Central gate. When an earthquake occurs, the proportion of people choosing to evacuate to the North Central gate increases, while the proportion of people choosing to evacuate to the Sakurabashi gate decreases to some extent. Whether under normal circumstances or earthquake conditions, the Sakurabashi gate is the main evacuation exit for people in the EKI MARCHE OSAKA food and shopping plaza.

As shown in Figure 5.12, we know that 69.23% of people chose to evacuate to the North Central Gate in both normal and earthquake situations. In normal circumstances, some people also chose to evacuate to the Sakurabashi Gate, Midosuji North Gate, and Midosuji South Gate. However, in the event of an earthquake, no one went to the Midosuji North Gate for evacuation, while the number of people going to the South Central Gate for evacuation increased. It is obvious that the North Central gate is the main exit selection for the people at platform 11 of JR Osaka Station.

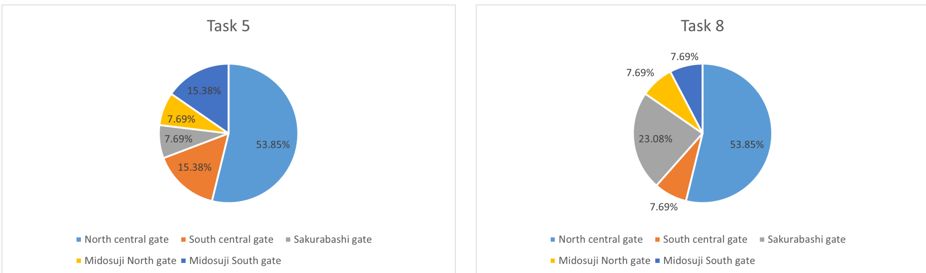

Figure 5.10: Comparison of Exit Selection of Task 5 and Task 8

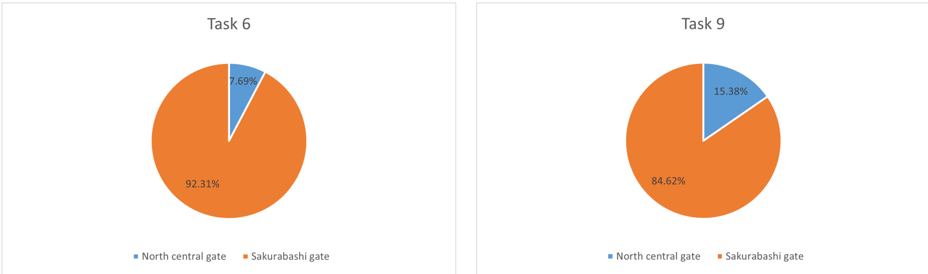

Figure 5.11: Comparison of Exit Selection of Task 6 and Task 9

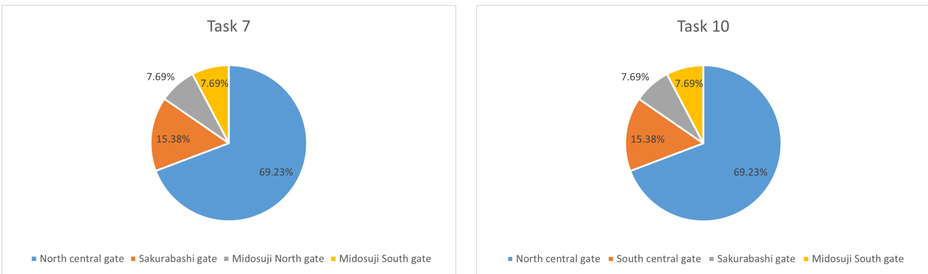

Figure 5.12: Comparison of Exit Selection of Task 7 and Task 10

Chapter 6

Conclusion

6.1 Conclusion

This study developed a simulated evacuation VR system for Osaka Station in Japan using Unreal Engine 4 and PICO 4 as development platforms. Different recording methods were used to collect a sequential dataset of evacuation behaviors of experiments with spatial completeness knowledge of Osaka Station in both real and virtual scenarios. Through comparison with the real situation, it was found that the evacuation behavior sequences presented by each experimenter in the VR simulated evacuation system in their fully familiar scenarios were basically 80% close to the evacuation behavior in the real situation. In the less familiar underground shopping mall scene, the evacuation behavior sequence presented in the VR simulation evacuation system is basically 66% close to the evacuation behavior in real situations. Based on user feedback and a detailed data comparison of behavior sequences in underground shopping mall scenarios, the impact of evacuation behavior on pedestrian flow and various products can distract the experimenter's attention in this system. Therefore, this is also one of the reasons why the similarity of simulated evacuation behavior sequences decreases compared to the previous situation. Then, to get the results of comparing the differences in evacuation behavior of experimenters between normal and earthquake conditions, we used the BSA-based method to explore the differences by analyzing the Leven-similarity in behavior sequences, differences in the average number of occurrences of specific behaviors, the impact of human flow on evacuation behavior, route selection, and exit selection in these dimensions. Thus providing effective data support for the improvement of the evacuation management system at Osaka Station. Regarding the impact of knowledge accumulation on the evacuation behavior of experimenters, we compared the route selection sequence and concluded through feedback from the experimenters that most people cannot remember their route after only experiencing it once in the Osaka station environment. And from the data we collected, we found differences in evacuation behavior in different environments at Osaka Station. That is, in environments with relatively simple spatial structures, especially in environments with only one floor, people's evacuation behavior is less affected by human flow compared to complex spaces and multi-layer environments. In relatively simple spatial environments, people who do not evacuate in the direction indicated by the safety exit information are also reduced.

6.2 Limitations

Due to limited equipment conditions, we used game controllers to map the experimenter's movement behavior to a simulated evacuation environment, and the seismic effect only affected the experimenter visually and audibly. And the number of experimenters we recruited is rather small, with a majority being international students. Consequently, the scope of the experimental subjects and data may be somewhat limited, given there are other groups of foreigners in Japan than international students.

6.3 Future Work

In future work, We hope to recruit more experimenters from various professions for experiments and improve the simulation evacuation system's ability to more accurately reproduce real-life situations. We hope to use more advanced equipment such as VR universal treadmills [47] to more accurately map people's movement behavior. For earthquake effects, we also hope to use some more advanced force feedback devices to enhance the physiological and psychological effects of earthquakes, so as to obtain more realistic evacuation behavior feedback data. At the same time, we also hope to improve the development of hardware devices such as graphics cards and CPUs, to enhance the development platform's carrying capacity for more NPCs, and more realistically reproduce the complex pedestrian flow situation of Osaka Station in real scenarios. At the same time, hardware improvements such as higher configuration graphics cards, higher configuration running memory, and larger storage space can also support development platforms with better-rendering effects, such as Unreal Engine 5[48].

Meanwhile, the behavior data of these experimenters can also be applied again to the NPCs in the system scenario, making their behaviors in the scenario more closely related to real-life situations. For example, the NPCs can also be set to follow the flow of people or follow the prompts of safety exit signs to find safety exits. In order to enhance the application scope of the system, we are considering conducting simulated evacuation training for Japanese locals who have more comprehensive disaster prevention knowledge and stronger evacuation capabilities in earthquakes. Through the training in evacuation behavior sequence and evacuation pathfinding sequence by these people, we aim to obtain the optimal solution for evacuation behavior and route selection in various scenarios as much as possible. Then, the optimal solution can be applied to the simulated evacuation environment to guide experimenters with weaker evacuation abilities, thereby improving their evacuation ability.

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