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Original Article

Development of human-in-the-loop experiment system to extract evacuation behavioral features: A case of evacuees in nuclear emergencies

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A B S T R A C T

Evacuation time estimation (ETE) is crucial for the effective implementation of resident protection measures as well as planning, owing to its applicability to nuclear emergencies. However, as confirmed in the Fukushima case, the ETE performed by nuclear operators does not reflect behavioral features, exposing thus, gaps that are likely to appear in real-world situations. Existing research methods including surveys and interviews have limitations in extracting highly feasible behavioral features. To overcome these limitations, we propose a VR-based immersive experiment system. The VR system realistically simulates nuclear emergencies by structuring existing disasters and human decision processes in response to the disasters. Evacuation behavioral features were quantitatively extracted through the proposed experiment system, and this system was systematically verified by statistical analysis and a comparative study of experimental results based on previous research. In addition, as part of future work, an application method that can simulate multi-level evacuation dynamics was proposed. The proposed experiment system is significant in presenting an innovative methodology for quantitatively extracting human behavioral features that have not been comprehensively studied in evacuation. It is expected that more realistic evacuation behavioral features can be collected through additional experiments and studies of various evacuation factors in the future.

1. Introduction

Evacuation time estimation (ETE) is essential to plan and implement effective protection measures during nuclear emergencies. Since evacuation must be completed before the emitted radioactive material reaches the affected area for effective protection measures, the evacuation time and problems associated with evacuation must be predicted and evaluated in advance as different issues may arise during real nuclear emergencies. Nuclear operators in South Korea should evaluate evacuation time for the emergency planning zone (EPZ) [1,2]. The evaluation can be used to appraise resident protection measures such as traffic control, shelter-in-place, and evacuation. In the United States, ETE evaluation is used to establish policies for emergency response by analyzing the risk level in each scenario [3].

Therefore, ETE evaluation should aim to identify factors that will impact residents' safety and produce high-fidelity prediction results. ETE evaluation should also analyze evacuation times under various emergencies, considering appropriate assumptions and uncertainties. In particular, evacuation behavioral features such as an individual's evacuation decision (e.g., whether to evacuate and exit choices) and time (e.g., risk recognition time, preparation time, and travel time) may affect the overall evacuation pattern. Thus, evacuation behavioral features were selected as major factors confirming whether real-world situations were adequately reflected, and these were largely divided into decision-making and temporal types. Despite the importance of evacuation behavioral features, the current ETE evaluation performed by nuclear operators in South Korea following radiological emergency regulations is based on simple assumptions that overlook such behavioral

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features. Existing evaluations conducted in many countries, including South Korea, mainly focus on traffic simulation. Although the evacuation behavioral features of individuals greatly influence evacuation patterns, they still rely on traditional methods such as surveys and interviews due to difficulty in measurement [4,5]. The importance of behavioral features can be confirmed through the results of previous studies on pre-evacuation time estimation: the total evacuation time increased by 18.99% whereas the appearance time of the highest density on the easy-congestion intersection decreased by 36.77% when the pre-evacuation time was considered [6]. However, relatively few studies have been conducted on evacuation behaviors such as pre-evacuation situations that require observation of individuals' immediate reactions [7]. Based on radiation disasters such as Three Mile Island and Fukushima, it was found that individual situational awareness without appropriate information at the beginning of emergencies led to evacuation disorders and serious damage [8]. At the time of the Fukushima disaster, residents evacuated based on their judgment in confusion without information about the seriousness of the situation or the hazards resulting from the delay of the official warning [7]. The large-scale shadow evacuations triggered by such limited information did not occur according to the government's plans; this resulted in more casualties during the evacuation process than in the disaster itself [9].

It is needed a lot of studies on protection measures considering behavioral features and circumstances of each evacuee during disasters, however, only a few data on them are available at the individual level due to the rarity and specificity of radiation disasters [10]. Therefore, this study intends to present a novel experimental system extracting behavioral features throughout the entire evacuation process. The estimation of evacuation behavioral features such as exit choices and evacuation time based on surveys widely used in previous studies differed from the actual scenarios [11]. Therefore, extraction of human behavioral features through the interaction between humans and emergency environments is essential, and hence a human-in-the-loop (HITL) concept that can effectively implement such interactions was introduced. The reproduction of environments that faithfully reflect real-emergency is crucial for identifying realistic behavioral features. To implement such environments, advanced VR technology was used, as virtual environments can safely extract evacuation behavioral features. Recent studies analyzing human behaviors in dangerous situations such as hurricanes and fires are overcoming the constraints of the experiment environment by using VR [12,13]. This study develops a HITL experiment system that extracts evacuation behavioral features from the interactions between human and virtual environments simulating nuclear emergencies. Regarding future work, an agent-based model (ABM) method that can simulate multi-level evacuation behaviors using collected HITL experimental data is proposed. This study is organized as follows: Section 2 summarizes related studies. Section 3 deals with the development of a HITL experiment system in detail and describes the experimental procedure. Section 4 provides the verification and comparative study of the developed experiment system by analyzing results. Section 5 presents an application of agent-based modeling and simulation, a new approach that can demonstrate evacuation behaviors at the multi-level analysis, and Section 6 discusses the proposed system compared to existing related studies and disasters to explain its novelty and proposes areas for future research.

2. Related works

Several evacuation studies have attempted to extract and analyze empirical behavioral features, however, most of them used traditional methods such as surveys. Among them, Chen et al. [14] collected responses related to tsunami evacuation through resident surveys. Evacuation distances, estimated times, evacuation destinations, and route choices were modeled, however, the study relied entirely on empirical evidence from residents. In contrast, Arias et al. [15] implemented fire disasters in physically existing high-rise buildings using two VR systems: Head Mounted Display (HMD) and Cave Automatic Virtual Environment (CAVE), and the experiments were conducted in each environment. The results show that the characteristics of different VR systems on participants' behavior were successfully analyzed, however, the environmental scope was limited to the building unit. This study aims to extract highly utilized human behavioral features for most residents in the target area among people who do not experience actual disaster situations. Therefore, it is necessary to effectively simulate and present nuclear emergencies using VR systems that are verified through existing studies [13,15]. The study for high-fidelity evacuation should propose different scenarios from previous studies so that behavioral features can be observed through organic interaction within VR in nuclear emergencies.

To explore approaches for analyzing evacuation dynamics from human behavioral features and demonstrating the scalability of the experiment system, previous studies that analyzed human evacuation patterns under a nuclear emergency in the same domain as this study was summarized. Many studies have developed multi-level simulations of evacuation dynamics using an ABM. Yang et al. [16] performed comparative experiments between several scenarios by combining a machine learning-based exit choice model with the pedestrian simulation using an ABM and applying the data collected from the serious game. Kim et al. [10] specifically dealt with social interactions among evacuation behaviors in terms of agent-based modeling and simulation. By using affordance-based finite-state automata, the decision-making process from situational awareness to the behavior of evacuees was properly expressed in an ABM. Based on the ABM, simulations were implemented to mathematically analyze the dynamics of social behavior. Hwang et al. [17] focused on traffic analysis, applied an ABM to traffic flow from a systematic perspective, constructed a simulation, and addressed the results based on several emergency scenarios. Particularly, the ABM considered expected damage to residents due to the spread of radioactive materials.

As described above, agent-based modeling and simulation are considered suitable for analyzing multi-level simulation and evacuation dynamics by reflecting individual behavioral features collected from the proposed experiment system as behavioral rules in agents. Therefore, agent-based modeling and simulation are used to demonstrate the scalability of the proposed HITL experiment system. The model and simulation are proposed as a method for analyzing evacuation dynamics. However, since this study focuses on the development of a HITL experiment system that extracts evacuation behavioral features, the research scope is limited to determining the possibility of application.

3. Methodology

This study focuses on methodology development that can extract realistic human behaviors during nuclear emergencies. The ultimate overall system consists largely of a HITL experiment system that collects human behavioral features and an agent-based modeling and simulation system that defines and simulates agent behavior models using the collected data (Fig. 1). First, nuclear emergency evacuation circumstances are implemented on VR. Then, the experiments are conducted using the VR-based HITL experiment system. Subsequently, an ABM is proposed as a method of utilizing the results for the large-scale evacuation patterns. This

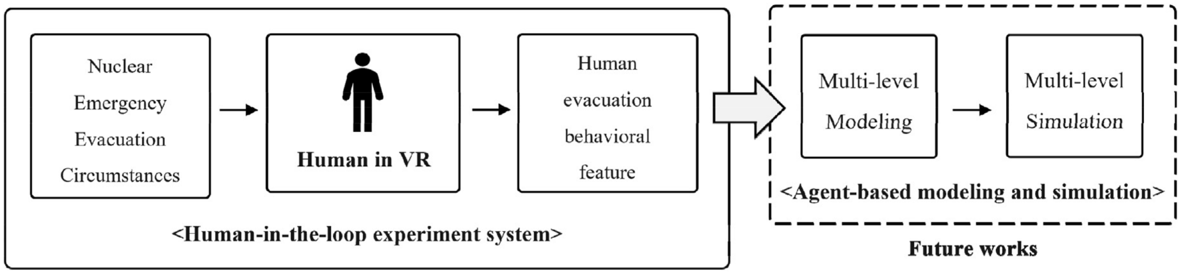

Fig. 1. Overall system implementation.

study focuses on VR-based HITL experiment systems that extract individual human behavioral features at the micro-level. The agent-based modeling and simulation system with HITL experiment system results are discussed in Section 5 as a part of future work after the results of the HITL experiment system are presented in Section 4.

3.1. Nuclear emergency evacuation circumstances

Nuclear emergency evacuation circumstances should be considered to provide a sense of immersion and plausibility. Scenarios based on the circumstances can be reproduced in VR. Four aspects of the disaster were analyzed to confirm the evacuation situation as shown in Table 1: Temporal, Geographical, Human, and Disaster. It is possible to define the representative scenarios with various conditions by reviewing the following main aspects.

Temporal aspects: An earthquake-induced nuclear emergency was assumed. The earthquake was used for the purpose of reproducing environmental cues associated with the start point of a nuclear emergency. Owing to the characteristics of the nuclear emergency, recognizing such an emergency is difficult for residents outside the nuclear facility site. In addition, the effects of earthquakes (e.g., tsunami and infrastructure destruction) must be considered, but were overlooked in this study. The time points are set to two circumstances based on the Fukushima case: when the earthquake occurred and immediately after the official evacuation order. The virtual environment also shows the social recognition situation between the two points in time, which relies on social interaction due to insufficient information and delayed evacuation orders. The participants respond according to critical parameters considered in the other aspects during the designed times. In the Fukushima case, the Japanese government gave the first evacuation order 6 h after the earthquake. However, the participants could not continue the VR experiments for that long, so the experiments lasted a few minutes. This time gap can be compensated close to the actual situation through calibration.

Geographical aspects: The part of the EPZ of the Kori Nuclear Power Plant (NPP) Site, Korea's representative NPP site, is the geographical background. The area is prone to considerable damage resulting from traffic congestion due to the high population density. For this reason, this area was chosen for this experiment. In the virtual environment, participants were provided a map with an NPP mark to enable them to select an exit, as shown in Fig. 2. They could recognize detailed information such as the distance from the NPP and assembly point location through the map. The exits lead to three assembly points designated by the local government and three express ramps for moving to other cities [18–20].

Disaster aspects: It is challenging to recognize radioactive materials using human senses, so this experiment was implemented with smoke and explosion sounds at NPP so it could be easily noticed. We also assumed external factors would significantly impact evacuees' judgment unless accurate and sufficient information was given, like in the Fukushima accident [7,9]. Therefore, external factors were also considered essential to represent disaster situations. The external factors included environmental, social, and official cues.

Human aspects: The Protective Action Decision Model (PADM), which deals with human response to disasters, was referenced [22]. According to the PADM, personal protection decision-making begins with environmental, social, and warning messages. Warning messages were modified to official cues considering the nature of radiation disasters. Regarding environmental cues, audiovisual elements such as smoke and siren were treated. Social cues demonstrated information dissemination and the disorientation of people through a TV. Lastly, official cues were provided as breaking news through a TV and a mobile phone.

Table 1
Main aspects for designing nuclear emergency evacuation.

Aspects	Considerations for scenario design
Temporal	After the magnitude 9.0 Mw (moment magnitude scale) earthquake occurs Until official evacuation order
Geographical	EPZ of Kori Nuclear Power Plant, Korea High population density
Disaster	Difficulty of cognition with human senses Systematic management of the government
Human	Protective Action Decision Model (PADM) Social interaction

3.2. Scenario settings

The main aspects considered in section 3.1 enable an immersive virtual environment in which participants can recognize and act. A scenario was presented sequentially to obtain well-organized and high-quality behavioral features from participants based on the implemented immersive virtual environment. The scenario was constructed focusing on the main events by analyzing the four main aspects identified above. First, the types of nuclear emergencies designated by the law in South Korea were reviewed to determine the cues [1]. Nuclear emergencies are classified into an alert, a site area emergency, and a general emergency depending on the severity and the degree of damage expected. An alert is a nuclear emergency in which the effects of a radioactive-material leak are expected to be confined to the building of a nuclear facility. The government receives and disseminates the NPP situation and launches initial response teams. The site area emergency is expected to be limited to the nuclear facility site following the impact of radioactive material leakage. In this situation, the government prepares protection measures, and residents closely monitor the situation and prepare for evacuation. The effects of radioactive material leakage are expected to reach outside the nuclear facility site in general emergencies. The government decides to take action to protect residents, and residents evacuate under the guidance of local governments. Considering temporal and disaster aspects, the

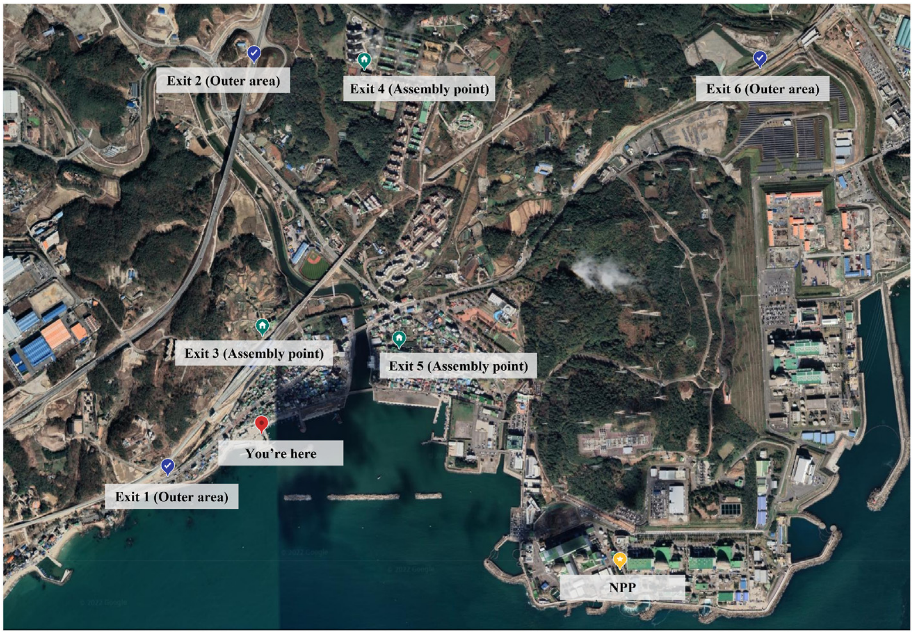

Fig. 2. Exit choice [21].

site area emergency (the initial time of an earthquake-induced nuclear emergency) and general emergency, which are nuclear emergencies that actually affect resident evacuation decisions, were set as the beginning and end of the scenario. The alert, which is expected to have no effect on evacuation behavior because no actual evacuation-related orders were issued by the government, was excluded from the scenario setting. Regarding human and disaster aspects, most residents begin to suspect danger through social networks during the time between site area and general emergencies. Social recognition is considered a key factor that influences evacuation behavior in disaster situations [23]. Additionally, social recognition was established to examine the impact of social interaction, a key characteristic of humans, on evacuation in situations where the information preceding the government evacuation orders is inaccurate and insufficient. The social recognition step is inserted to detect behavioral features when risk is noted through social messages from a TV and a mobile phone. The factors that influence evacuation behavior and unexpected movements such as self-evacuation could be captured during site area emergencies, social recognition, and general emergencies.

i) **Site area emergency**: Participants in an indoor environment could be aware of a site area emergency through disaster broadcasting and text messages from a mobile phone. The broadcast announced that radioactive material has not leaked to the outside, hence, the government orders them to wait inside the building. Participants noticed the abnormal situation through environmental cues such as siren sounds and smoke from the NPP.
ii) **Social recognition**: Some residents who detected the abnormal situation started evacuating. TV broadcast shows the continued evacuation despite the government's order to remain inside the house. The mobile phone also demonstrates that people were updated about evacuation situations via.
iii) **General emergency**: The government provides an immediate evacuation order through disaster broadcasting and text messages.

3.3. VR-based human-in-the-loop experiment system

This section provides configuration details in the HITL experiment system. Fig. 3 presents the proposed HITL experiment system consisting of virtual environments and human interactions that reproduce nuclear emergencies. The immersive nuclear emergency evacuation scenarios in the virtual environment enable us to collect evacuation behavioral features. The virtual environment provides immersive evacuation situations through systematic scenarios deployment. Furthermore, the configuration shown in Fig. 4 describes the implementation of the scenario in virtual environments. VR simulations were developed using Unity™ of Unity Technologies. The virtual environment based on the real world represents nuclear emergency scenarios (Section 3.2) by appropriate main cues arrangement, including environmental, social, and official. There are both indoor and outdoor virtual environments. Participants can move by walking and respond to scenarios by interacting with objects. Social and official cues were presented through media such as a TV and a mobile phone. Environmental cues showed that smoke and sirens from the NPP were presented outside the window. The geographical background was implemented through 3D modeling based on satellite image-based geographic information. Building, human, and vehicle objects were created using commercial Unity Assets, and essential facilities such as Wollae Station and Kori NPP were made similar to their actual appearance. The road was constructed based on the actual location and features. Participants who decided to evacuate could take evacuation actions through exit choice and driving.

The role of the user interface (Fig. 5) is to facilitate interaction between participants and the virtual environments. The interface can be divided into the cognition part for recognizing emergency scenarios and the controller part for handling the virtual environments that reproduce nuclear emergencies. The hardware of the cognition part used VIVE Cosmos Elite™ from HTC Corporation. The system consists of a HMD and base stations for lighthouse tracking, which can recognize the virtual environment through audiovisual. Depending on the situation, participants can make

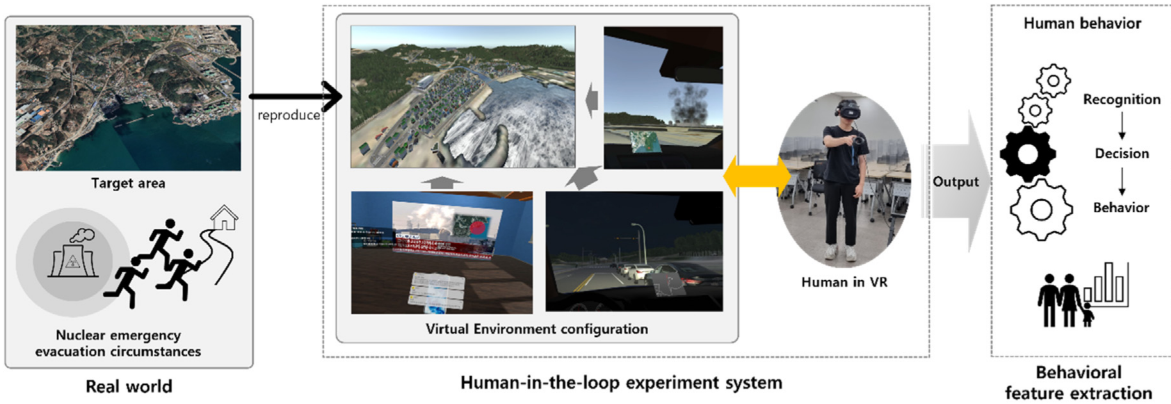

Fig. 3. VR-based HITL experiment system configuration.

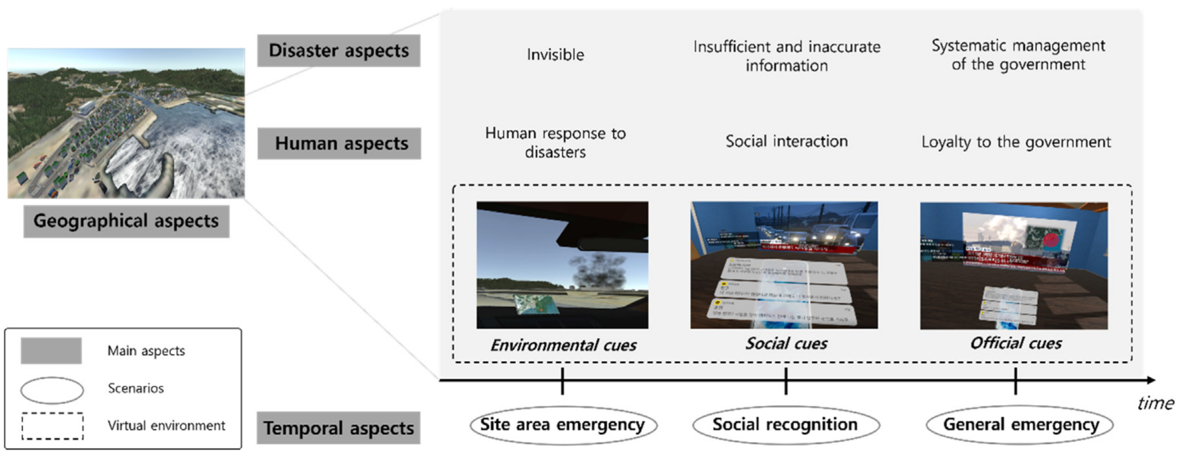

Fig. 4. Main aspects (Section 3.1) and scenarios (Section 3.2) of virtual environment configuration.

their decisions in the indoor environment through a controller and in the outdoor environment using a steering wheel. The steering wheel used Logitech Corporation's G29.

The proposed HITL experiment system can extract human behavioral features by interacting with virtual environments (see Fig. 7). The human behavioral features were reviewed based on time and the decision-making process aspects by referring to ETE criteria [3]. This methodology gives us more realistic responses compared to the existing survey method confirmed through the data list in Table 2. In addition, the data in Table 2 that can be extracted through this VR system was drawn (as shown in Fig. 6) along with the overall system structure.

Fig. 5. User interface in HITL experiment system.

Evacuation time is divided mainly into risk recognition, preparation, and travel time. Participants faced physical and mental difficulties in the VR experiment for a long time, and the reliability of the results cannot be verified. In evaluating time in this study, it is estimated that the risk recognition time is the same as the evacuation decision time, which is the time from the start of each scenario until a door or a bag is selected. The assumption was that participants either prepared for evacuation or evacuated immediately because they recognized the danger. Another assumption is that such behavior is represented by choosing doors that allow immediate evacuation or choosing a bag to gather belongings in VR experiments. The preparation time is set to zero when evacuating immediately and set to the interaction time when packing the bag. The maximum interaction time is applied based on the selected bag capacity (small: 5 min, medium: 10 min, large: 20 min), showing accumulated time during triggering the controller. The actual preparation time was calibrated by assuming 30 times the time measured in VR. The maximum preparation time was set to 20 min, like in the Fukushima case [24]. Travel time was determined by selecting an exit that leads to the destination. All times were collected in seconds up to the two decimal places.

3.4. Experiments

3.4.1. Participants

There were 17 undergraduate and graduate students who

Table 2
Data descriptions from the proposed system.

Type	Variables	Description
Time	Risk recognition time	Time spent recognizing risks and determining evacuation
	Preparation time	Evacuation preparation time as interaction time with objects after evacuation decision
	Travel time	Time to travel to selected destination by driving
	Indoor residence time	Total time spent in an indoor environment
	Outdoor residence time	Total time spent in an outdoor environment
decision	Evacuation cue	Factors that determine evacuation among cues presented in the order of time
	Self-evacuation	Evacuation situation prior to official order
	Exit choice	Destinations want to evacuate outdoors

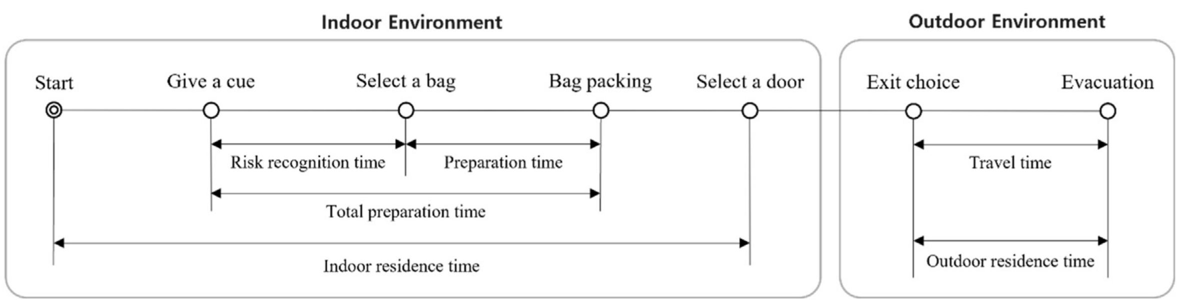

Fig. 6. VR system configuration.

Fig. 7. Snapshot of the indoor/outdoor virtual environment from the HITL experiment system.

participated in this study. All participants were male, with an average age of 26.3 and a standard deviation of 2.86. They were informed of the basic guidelines and were asked for simple personal information. They all participated in a control and an experimental group environment, each being a tutorial and the main environment. This study was approved by the Institutional Review Board. The aim of these experiments is to verify the developed experiment system for certain age groups rather than analyzing the evacuation behavioral features in a diverse group of evacuees.

3.4.2. Experiment procedure

We conducted the experiments to verify the developed experiment system. This was done to extract evacuation behavioral features from nuclear emergencies based on evacuation cues presented in the order of time. Accordingly, all participants participated in the experiment with evacuation scenarios after indoor-outdoor tutorials, as shown in Fig. 8. The tutorial presents the same spatial background as the main environment, excluding the radiation situation so that participants could be familiar with VR devices and the environment. In addition, the participants drove to a given destination to create the feeling that they lived close to the NPP. As shown in Fig. 8, the experiment was based on the participants' decisions to evacuate.

The scenarios in Section 3.2 were presented over a set time in the following order: i) site area emergency, ii) social recognition, and iii) general emergency, if there was no evacuation. A certain amount of time was given between each situation so that the participants could understand the situation and decide on their actions. If they evacuated in the middle of the scenarios, the following evacuation scenario in the indoor environment was not provided. The outdoor environment is presented only to the evacuated participants. Even in the general emergency, participants who chose to stay inside the house were determined not to have evacuated and the experiment was immediately ended.

4. Human-in-the-loop experiment system verification and comparative study

The results of the experiment showed that the behavioral features according to the nuclear emergency scenarios given in the order presented in Fig. 8 were properly extracted following the system design. Simultaneously, the extracted behavioral features were compared and analyzed against existing studies.

In the experimental data, two participants failed to complete the evacuation task under the government's evacuation order in the general emergency scenario due to their misunderstanding of the VR operation and scenario. Therefore, data analysis was performed on 15 people, excluding incomplete data from the participants. Risk

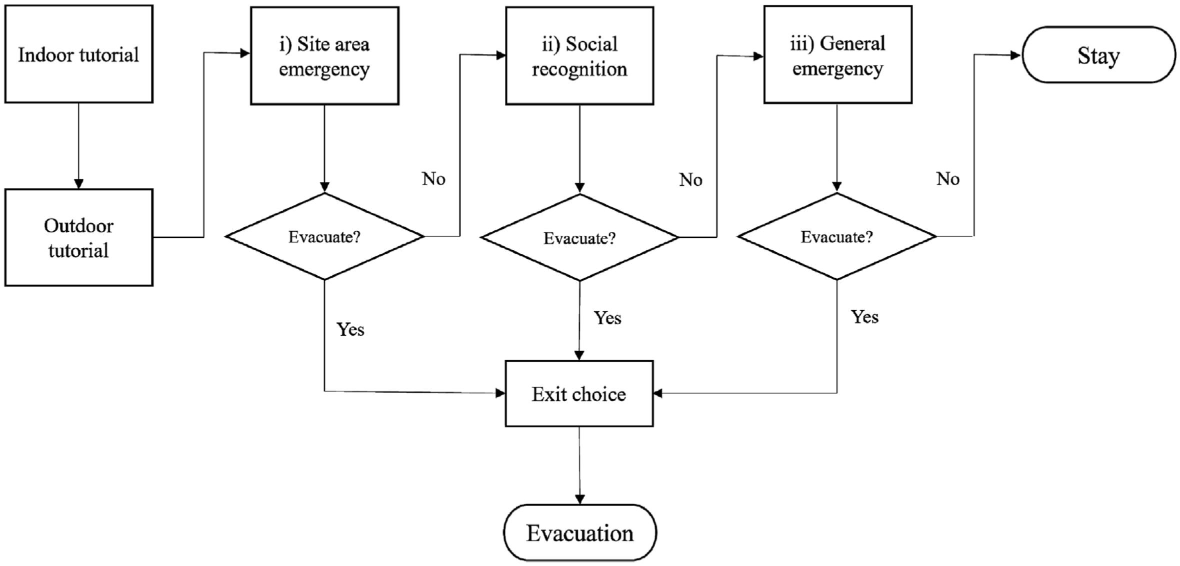

Fig. 8. Experiment flowchart.

recognition and travel time were measured based on real-time and preparation time was adjusted to 30 times the VR time to calibrate the actual time. This experiment was designed for humans and was therefore calibrated by selecting multiples to finish the experiment within an appropriate time to avoid VR sickness [25].

4.1. System verification

The results were evaluated by three groups according to the time point of the evacuation decision to check whether the HITL experiment system effectively reproduced the nuclear emergencies. The first group is the site area emergency group, which evacuated despite the government's order. The second group is the social recognition group, which decided to evacuate after contacting their acquaintances that were evacuating and watching the broadcast of the evacuation procession. The general emergency group evacuated according to the government's evacuation order. Of the 15 evacuees, nine were evacuated from the site area emergency, three from social recognition, and three from the general emergency. Nine evacuees moved to the exit of the express ramp, which allowed them to shift to the outer area, and six moved to government-designated assembly points. Thirteen evacuees chose the exit far from the NPP, and two other evacuees also tried to move farther through the assembly points.

The proposed system was verified by reviewing the indoor and outdoor residence time distribution by a group as a box plot, as shown in Fig. 9. Regarding indoor residence time, since the scenario is presented in order, a time delay can be confirmed in groups. The times of the social recognition and the general emergency group overlap due to the differences in the preparation time. As Group 1 evacuated in response to the first given signal, evacuation-related actions proceeded faster than those of Groups 2 and 3, and hence the indoor residence time was shorter than those of the other groups. Concerning outdoor residence time, the residence time was long in all groups as most participants chose a far exit.

The results were also statistically analyzed using ANOVA to compare and analyze three groups. The p-value associated with the indoor residence time was significantly low ($P < .001$), confirming the difference between groups. Regarding outdoor residence time, the p-value was insignificant ($P = .923$), thus, the difference between groups could not be confirmed. Although the experiment was conducted on a small number of people, the proposed HITL experiment was demonstrated as a result of indoor and outdoor residence time that depends on the participants' decision. In addition, evacuation behavioral features to determine distance

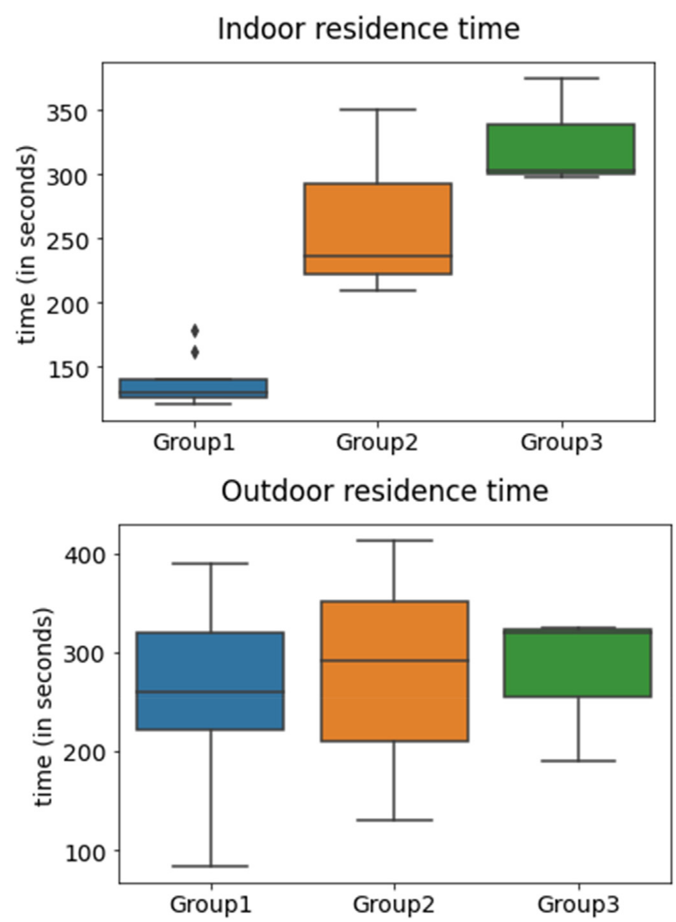

Fig. 9. Box plot of indoor and outdoor residence time by groups (Group 1: site area emergency group, Group 2: social recognition group, Group 3: general emergency group).

Table 3
Risk recognition, preparation, travel time analysis.

Categories	Distribution	Percentage (no. Of samples)
Risk recognition time	<=20.00s	40.00% (6)
	20.00s–40.00s	33.33% (5)
	>=40.00s	26.67% (4)
Average / Std	30.15s / 24.04	
Preparation time	400.00s	20.00% (3)
	800.00s	40.00% (6)
	1200.00s	40.00% (6)
Average / Std	716.00s / 376.56	
Travel time	<=200.00s	26.67% (4)
	201.00s–300.00s	26.67% (4)
	301.00s–400.00s	40.00% (6)
	>=400.00s	6.67% (1)
Average / Std	265.75s / 93.45	

from danger were effectively tracked as in previous studies through the statistical result of the outdoor residence time [26].

4.2. Comparative study on experimental results

The results of the experiment were comparatively analyzed against previous research. Table 3 shows the statistical analysis of time data without normalization. Fig. 10 shows the density curve using a kernel density estimation method to analyze the distribution. The data in Fig. 10 were normalized to conduct a comparison between the three types of time data with different scales. The risk recognition time and preparation time are distributed in the early hours, while travel time is distributed relatively in the late hours. It is believed that people take nuclear emergencies more seriously than other disaster situations by making quick evacuation decisions and preparations.

In most studies, risk recognition time and preparation time (such as bag packing and gathering family members) are reviewed together [27], so the total preparation time was calculated as the sum of both times for comparison and is shown in Fig. 10. Although the total preparation time and preparation time differ from the values shown in Fig. 6, they exhibited similar patterns due to the influence of the relatively long preparation time and normalization. According to the Fukushima case, excluding those who did not evacuate, the rate of immediate evacuation was 17.04%, the rate of evacuees within 20 min was 56.37%, and the rate of evacuees exceeding 20 min was 26.59% [24]. Thus, 73.41% of them were evacuated within 20 min, which is similar to the results of this experiment (Fig. 10), where the graph is skewed to the left. The results are also supported by comparisons with expected completion preparation times in virtual NPP cases (within 2 h) and hurricane cases (7.5 h) [28].

In the case of evacuation situations in buildings [29] or natural disaster situations [30], there is a high tendency to choose the nearest destination. However, in the case of nuclear emergencies, the risk of radiation exposure was reduced in inverse proportion to the distance, so there was a relatively high tendency to evacuate to a destination far from the radiation risk area [26]. The results of this study also confirmed the tendency to avoid dangerous areas based on the analysis of many participants choosing an exit far from the NPP using the provided map with the NPP mark. Since this study was conducted on people who do not live near NPP, there may be some differences from the actual situation. However, as previous studies have confirmed, people living remotely travel farther than those living near NPP [31,32]. In future studies, the evacuation mechanism can be explained by considering the demographic factors (e.g., age, knowledge, and physical condition) near the NPP area and the level of fear of radiation.

5. Application suggestions on future work: agent based modeling and simulation for evacuation dynamics analysis

Although the HITL experimental system can confirm the occurrence of micro-evacuation behavior at the individual level, the prediction of multi-level evacuation dynamics is limited. Analysis of evacuation-behavior dynamics at the macro-level is necessary in the evaluation of ETE, and hence ABM research is proposed by reflecting the HITL results as a future study for this purpose. The ABM is effective in confirming the large-scale movement of the entire system in which agents interact with each other. For example, in the case of no official evacuation order, policymakers

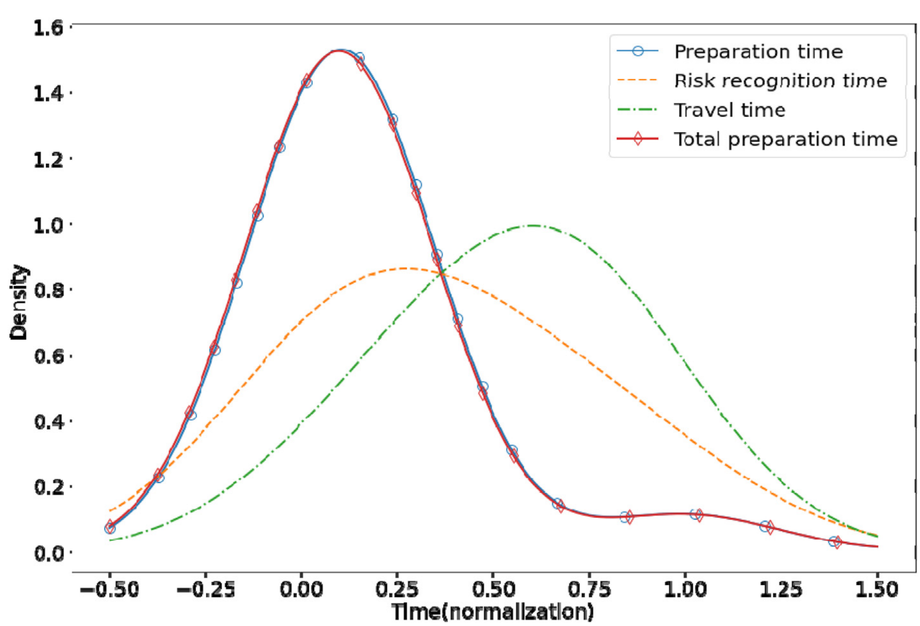

Fig. 10. Density curves of measured time with normalization.

want to ascertain the degree of initial evacuation delay to reduce the expected damage caused by self-evacuation. To this end, the ABM can establish a network that checks physical and social interactions in the background of the EPZ of Gori NPP. Evacuation information can then be tracked by selecting the main factors that lead to evacuation delays. Previous studies have implemented evacuation models based on surveys and assumptions of evacuation behaviors exhibited by agents. However, reflecting the behavioral features identified through the HITL experimental system can contribute to the analysis of more realistic and effective evacuation dynamics than those considered by models based on assumptions and surveys [10]. For example, utilizing the strengths of the ABM, which can reflect different behavioral features for each agent, the evacuation decision time and exit can be applied differently based on the results of HITL for each agent. The evacuation decision can also be set in various ways through interaction between agents. This detailed model design allows more effective assistance than that possible with other designs by identifying multi-level evacuation patterns. Moreover, the application of reinforcement learning on an ABM for large-scale evacuation dynamics can result in a more precise model than those currently available for policymaking [33].

The ABM reflecting the extracted behavioral features can also simulate evacuation dynamics in emergencies. Future studies should also model this with the expected casualty rate, self-evacuation, and resulting aggravated congestion taken into consideration. The ABM can be useful in proposing a new approach for conducting a multidimensional analysis in the event of a disaster and evaluating the scalability of the HITL experiment system. In particular, the ABM can analyze complex human evacuation processes at a spatial-temporal level, helping to mitigate damage and allowing appropriate measures to be taken in advance [10].

6. Discussion and conclusion

This study developed a VR-based HITL experiment system that can collect evacuation behavioral features by effectively simulating nuclear emergencies. The experiment system shows that behavioral features can be quantitatively extracted in disaster situations. The results of the experiment system can be used in an ABM to simulate evacuation dynamics. The proposed integrated framework showed the feasibility of its application in nuclear emergencies. This experiment system provides a novel approach for extracting realistic responses to disasters by covering pre-evacuation situations with immersive virtual environments unlike previous studies [4,16,17]. The proposed experiment system confirmed that 80% of participants began evacuating in the absence of an official evacuation order from the government. This far exceeds the shadow evacuation rate of 20% presented in NUREG/CR-7002 [3], which is used in ETE research. Despite the difference between shadow evacuation and self-evacuation, the commonality of non-compliance with government orders indicates that, in an actual nuclear emergency, a significant number of people can be evacuated without government orders. This evacuation would include moves to a far place very quickly, but, only 40% of the participants moved to designated assembly points, which is expected to disrupt the government's response. Thus, nuclear operators need to conduct further studies of self-evacuation as well as shadow evacuation rates by analyzing evacuation dynamics in case of an emergency. Government officials should also consider the high percentage of residents who do not follow the government's guidelines, and accordingly conduct appropriate disaster prevention drills and effective action manual revisions.

The proposed experiment system provides new technological developments and also presents an innovative methodology that can effectively consider human behavioral features that have not been previously addressed in evacuation studies. Although the analysis of evacuation dynamics was only suggested as a part of future work, the possibility of analysis was confirmed by providing ABM designs and simulation guidelines. Future research should consider experiments reflecting the demographic characteristics of the NPP area and various factors such as fear of radiation and financial issues [6,26]. A survey on citizen awareness of nuclear emergencies conducted in the Kori NPP area revealed that the negative perception of NPPs and concerns about nuclear accidents were relatively high, with a mean score of 4.27 out of 5. Moreover, the trust in information related to NPPs was low, with a mean score of 2.84 out of 5 [34]. Further academic research is necessary due to the significant impact of these negative psychological effects on actual evacuation behavior [11]. These improvements can help in the development of practical decision support and emergency management tools. The proposed experiment system is expected to provide an innovative methodology that can simulate complex and uncertain human behavioral features for effective disaster management.

Declaration of competing interest

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

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