Decision-Making Under Uncertainty in Tsunami Evacuation: Individual Differences in Information Consultation and Risk Perception

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Abstract

In tsunami evacuation, the two fundamental strategies are horizontal evacuation (moving away from the coastline toward a safer inland location) and vertical evacuation (moving to the upper floors of a building). However, few studies have investigated how individuals make decisions when both strategies are simultaneously available. This study examines how individual differences in lead-time information consultation and in degree of risk aversion affect strategy selection when evacuation begins from inside a high-rise building. A virtual reality (VR) experiment was conducted in an urban environment with 88 participants. Participants evacuated from a seven-story building under three location conditions: Near the Sea, Intermediate, and Near the Mountain. The results revealed that in the absence of lead-time information consultation, participants predominantly opted for vertical evacuation, relying primarily on the perceived safety afforded by the building's elevation. In contrast, when participants consulted the lead-time information, they tended to select horizontal evacuation. In addition, participants with a higher degree of risk aversion were more likely to select vertical evacuation, but only in the Intermediate condition, where the environmental cues were most ambiguous. These results suggest that individual differences (i.e., information consultation and risk perception) play an important role in evacuees' decision-making. Overall, the findings indicate that providing personalized information suited to evacuees' situations can reduce the influence of individual differences and support safer evacuation decisions.

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1 Introduction

1.1 Uncertainty in Tsunami Evacuation Strategy Selection and Individual Differences

In tsunami evacuation, selecting a safer destination is crucial to survival. Horizontal evacuation and vertical evacuation are the two fundamental strategies. Horizontal evacuation involves moving away from the coastline to a safer inland location, while vertical evacuation involves moving to the upper floors of a building. While staying in a high-rise building avoids the immediate risk of tsunami submersion, it may entail long-term risks such as structural collapse or isolation (e.g., shortage of relief supplies). Therefore, if time permits, moving to a safe inland area through horizontal evacuation may be considered the safest option.

From a motivational perspective, people who select horizontal evacuation tend to question the structural safety of tsunami vertical evacuation buildings and believe that inland areas can be reached before the tsunami arrives. On the other hand, those who opt for vertical evacuation tend to estimate that reaching inland areas before the tsunami arrival is difficult [4]. Generally, horizontal evacuation involves extended travel times but provides higher destination safety. Conversely, vertical evacuation requires minimal travel time but presents greater ambiguity regarding long-term safety.

Evacuees' geographic location (e.g., coast vs. inland) may significantly affect their perception of inland reachability. However, when geographical cues are ambiguous – for example, when evacuees are located at an intermediate distance from both the coast and high ground – they must make a decision under two uncertainties: the possibility of reaching the destination before the tsunami arrival ("reachability") and the safety of the destination ("safety"). Under such uncertain circumstances, individual differences may play an important role in their decision-making. Reachability can be evaluated by comparing the time required to reach the evacuation site (lead-time) and the tsunami arrival time [8]. Individual differences in the use of available evacuation information may influence how evacuees cope with this uncertainty. Indeed, reviewing the evacuation plan on the floor map has been shown to influence subsequent route selection during an emergency [7]. In addition, evacuees' degree of risk aversion may affect their decision-making, as the two strategies involve different types of risk [6]. However, the influence of these individual factors on tsunami evacuation strategy selection remains poorly understood.

1.2 Study Objectives

This study aims to address two questions in tsunami evacuation. First, it examines how multiple uncertainties and the trade-offs between the two strategies affect evacuees' strategy selection. Second, it investigates how individual differences in information consultation and risk perception affect strategy selection. To address these questions, an experiment was conducted in a desktop-based virtual reality (VR) environment, in which participants were required to evacuate in response to a tsunami under several scenarios. The experiment assumes evacuation from a high-rise building, where the building's height already provides a certain level of safety. In this context, this study investigated how consulting lead-time information and participants' degree of risk aversion affect the selection between staying in the building (vertical evacuation) and moving to a distant inland area (horizontal evacuation). Furthermore, from the perspective of behavioral geography, this study discussed how participants interpreted the available information and how these interpretations influenced their final strategy selection.

2 Methods

2.1 Participants and Materials

Data were collected from 88 participants aged 19 to 64 years (42 males and 46 females; M_{age} = 38.9 years; $SD = 9.95$) recruited through an online platform. All participants were native Japanese speakers, and the experiment was conducted in Japanese.

A virtual city was designed as a coastal city between the sea and the mountains (Figure 1). It was modeled using Rhinoceros 8 and imported into Unity, which was used to implement the experimental software. Each participant completed the experiment remotely using their own personal computer, without direct in-person supervision by the researchers. They moved within the environment using the keyboard (WASD keys) and controlled the view using the mouse. Movement speed was limited to walking (2.0 m/s) and running (4.3 m/s). Participants' position and viewing direction were recorded at 10 fps.

2.2 Experimental design

An area of high ground on the mountainside served as the destination for horizontal evacuation. Three high-rise buildings were placed at different locations: Near the Sea, Intermediate, and Near the Mountain (Figure 1). These target buildings were seven stories tall and high enough to remain safe from tsunami flooding. In each trial, the tsunami evacuation began inside one of them, and the rooftop of that building served as the destination for vertical evacuation.

A map of the city was displayed on the wall of the room where the evacuation began, and participants were free to consult it (Figure 2). The map provided the lead-time that served as critical temporal information regarding destination reachability, along with a simplified bird's-eye view of the city, the participant's current location (i.e., the location of the building), a marker for the evacuation site on the high ground, and an arrow indicating the route. While the primary function of a map is to provide spatial information, we designed the virtual environment with a simple grid-like structure and included a practice phase to familiarize participants with the environment beforehand. Consequently, participants were expected to have sufficient spatial knowledge, allowing the map to function primarily as a source of temporal information. This enabled us to analyze whether consulting the lead-time information via the map influenced participants' evacuation strategy selection.

Participants were instructed to complete the evacuation before the tsunami's arrival time, which was displayed on the screen at the beginning of the evacuation. To equalize the temporal difficulty of evacuation across all location conditions (i.e., to avoid a situation where horizontal evacuation would be easier when starting from the Near the Mountain condition), the tsunami arrival time was adjusted for each condition so that the lead-time margin (the tsunami arrival time - the lead-time) was fixed at 2 minutes.

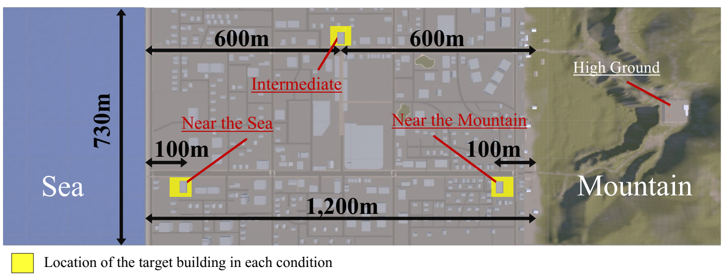


Figure 1 Environmental layout and locations of the evacuation buildings under three conditions.

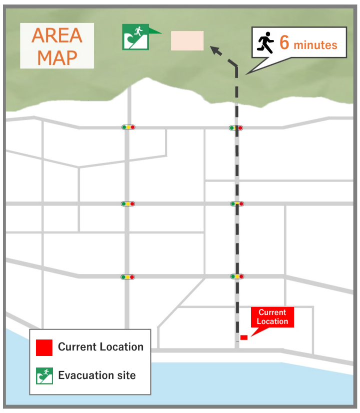


Figure 2 Map of the city (Near the Sea condition). The original text on the map was in Japanese and has been translated into English.

Table 1 Location conditions and evacuation timing parameters.

Location Condition	Tsunami Arrival Time [min]	Lead-Time [min]	Lead-Time Margin [min]
Near the Sea	8	6	2
Intermediate	6	4	2
Near the Mountain	4	2	2

2.3 Procedure

The experiment consisted of three phases: practice, main task, and questionnaire survey.

Practice. First, participants completed an item collection task in the same virtual city used in the main task. During this task, they collected capsule-shaped objects placed throughout the city one by one. Through this task, participants familiarized themselves with the movement speed and the scale of the city. They also gained prior knowledge about the structure of the city, including the two possible evacuation sites, i.e., the high ground and the rooftops of the target buildings, that would appear in the subsequent main task. Additionally, task completion times were recorded.

Main task. The main task was repeated three times, once for each location condition shown in Figure 1. In each trial, participants started from a location near the target building assigned to that condition. They were guided to enter the building and instructed to complete a dummy task requiring them to head to a designated room on the seventh floor and open the window. When they entered the room, a map showing lead-time information was visible on the opposite wall, but they were not explicitly instructed to consult it. Immediately after completing the dummy task, an earthquake occurred, represented by a shaking view on the screen and the sound of the earthquake warning alert. Once the shaking subsided, a major tsunami warning was issued, after which the tsunami arrival time was displayed on the screen, and participants were instructed to evacuate to a safer location. Participants then began moving toward the evacuation destination they considered safest. Each trial terminated when the participant completed the evacuation or when the tsunami arrival time had elapsed. The main task ended after trials in all location conditions were completed. To avoid order and learning effects across location conditions, the order of the trials was randomized for each participant.

Questionnaire survey. After the main task, participants completed a questionnaire. It assessed demographic information (age and gender); experience with and knowledge of tsunamis; usability of the movement controls and perceived realism of the experimental environment (both rated on a five-point Likert scale); and self-reported behavioral aspects during the experiment, such as their reasons for strategy selection and whether they had consulted the map. In addition, participants completed a binary-choice task designed to measure their degree of risk aversion [1], which is based on expected utility theory.

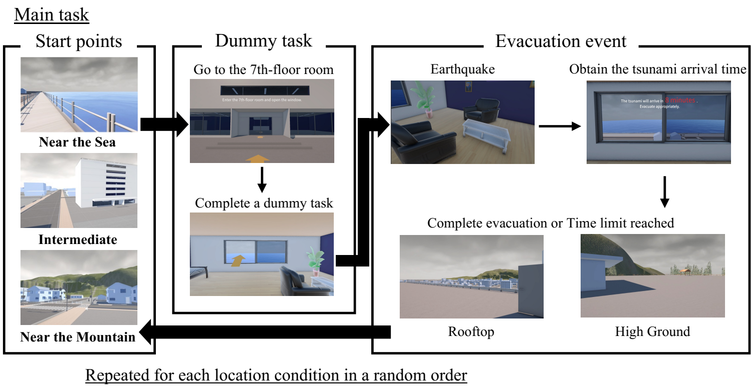


Figure 3 Workflow of the main task.

2.4 Analysis

Evacuation Strategy Selection Rates. For each location condition, the proportions of horizontal and vertical evacuation strategy selections were compared using binomial tests. To evaluate the effect of information consultation, trials were categorized into two groups based on whether participants consulted the map or not, as determined by the duration of the virtual camera orientation toward the map exceeding a predefined threshold and questionnaire responses.

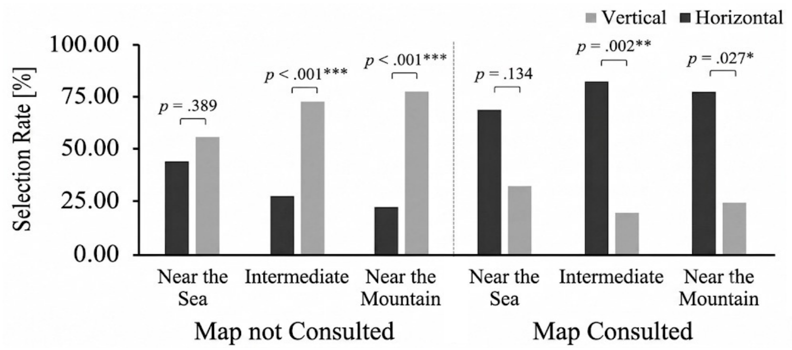
Generalized Linear Models. In addition, generalized linear models (GLMs) for each location condition were constructed to examine the effects of the multiple factors. The response variable was the selected evacuation strategy, with horizontal evacuation coded as 1 and vertical evacuation coded as 0. Explanatory variables included map consultation and risk aversion, the central concerns of the study, along with demographic factors known to be associated with navigation behavior, namely age and gender (male = 1). The completion time of the item collection task was also included as an index of operational proficiency in movement control in the virtual environment, with shorter times indicating higher skill.

3 Results and Discussion

3.1 Trends in Evacuation Strategy Selection Rates

Figure 4 shows the results of the binomial tests. Participants who did not consult the map selected vertical evacuation significantly more often in the Intermediate and the Near the Mountain conditions (both $p < .001$). Without the lead-time information presented on the map, participants had to estimate the travel time based only on their own sense of distance. They likely relied on the building's height, which was more obvious than the time needed to evacuate horizontally. Indeed, "building height" was the most frequently reported reason for selecting vertical evacuation in the questionnaire, which is consistent with previous research [3]. Additionally, participants were already at a high elevation when the evacuation began. This may have induced status quo bias [5] and loss aversion [2], which may have deterred participants from moving outside at the cost of their current perceived safety.

In contrast, participants who consulted the map selected horizontal evacuation significantly more often in the Intermediate and the Near the Mountain conditions ($p = .002$ and .027, respectively). By comparing the lead-time information with the tsunami arrival time, they were able to estimate the lead-time margin. This suggests that such objective information effectively reduced the uncertainty regarding reachability and may have replaced the subjective assessment of reachability. In other words, even when the building they are in offers a certain level of safety due to its elevation, people may select a safer evacuation destination if they can obtain clear and reliable information about the time margin.



* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 4 Results of binomial tests for evacuation strategy selection rates.

3.2 Effects of Individual Differences on Strategy Selection

Table 2 summarizes the fitted GLMs. The effect of map consultation was significant in the Intermediate and Near the Mountain conditions (both $p < .001$), which is consistent with the results of the binomial tests. Although the effect was not significant in the Near the Sea condition, a weak tendency was observed ($p = .058$). In this condition, the imminent visual and geographical threat of being very close to the sea may have had a more dominant influence on participants' decision-making than objective numerical information (i.e., lead-time on the map). These results suggest that consulting the lead-time information may promote horizontal evacuation across location conditions. However, this study did not collect qualitative data on participants' reasoning; therefore, we cannot determine why participants chose whether to consult the map. Future studies should investigate the factors underlying map-consultation behavior by collecting open-ended responses about participants' decision-making processes.

In addition, participants with a higher degree of risk aversion were significantly more likely to select vertical evacuation. This effect was observed exclusively in the Intermediate condition ($p = .040$). In the Near the Sea and Near the Mountain conditions, geographic factors, namely the distance to the sea and to the high ground, may have had a stronger influence on decision-making. In contrast, in the Intermediate condition, where such geographic factors were weaker, individual differences may have played a more important role in decision-making.

Furthermore, older participants selected vertical evacuation significantly more often in the Intermediate and the Near the Mountain conditions ($p = .032$ and $.044$, respectively). This may reflect older participants' greater concerns about the physical demands of horizontal evacuation, including longer travel distance and time, as well as a fear of struggling to navigate the VR environment due to a lack of gaming experience.

Table 2 Summary of the fitted GLMs for evacuation strategy selection.

Location Condition	Variable	β	*SE*	*OR*	p
Near the Sea	(Intercept)	2.902	1.504	18.215	0.054
	Map consultation	1.080	0.569	2.946	0.058
	Risk aversion	-0.202	0.120	0.817	0.092
	Age	-0.040	0.024	0.961	0.101
	Gender (male = 1)	0.742	0.488	2.100	0.129
	Operational proficiency	-0.056	0.089	0.946	0.530
Intermediate	(Intercept)	3.528	1.713	34.041	0.040^{*}
	Map consultation	2.702	0.671	14.903	$< 0.001^{***}$
	Risk aversion	-0.297	0.145	0.743	0.040^{*}
	Age	-0.061	0.028	0.941	0.032^{*}
	Gender (male = 1)	0.518	0.558	1.678	0.354
	Operational proficiency	-0.050	0.101	0.951	0.618
Near the Mountain	(Intercept)	1.897	1.701	6.665	0.265
	Map consultation	2.496	0.659	12.129	$< 0.001^{***}$
	Risk aversion	0.038	0.139	1.039	0.784
	Age	-0.061	0.030	0.941	0.044^{*}
	Gender (male = 1)	0.743	0.555	2.102	0.181
	Operational proficiency	-0.130	0.106	0.878	0.219

$^{*}\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$

4 Conclusion

This study examined the selection of tsunami evacuation strategies when evacuation begins from a high-rise building by conducting a desktop-VR experiment. The results showed that participants who did not consult the map tended to select vertical evacuation by relying on the elevation of the building. In contrast, when they were able to estimate the lead-time margin from the temporal information, horizontal evacuation was selected more often, across all location conditions. In addition, individuals' degree of risk aversion affected strategy selection when the environmental cues were ambiguous (i.e., the Intermediate condition).

These findings indicate that individual differences, including information consultation and risk perception, may play an important role in tsunami evacuation decision-making under uncertainty. This suggests that some individuals may make unsafe decisions. In this context, providing information may effectively mitigate the influence of individual differences and encourage safer evacuation strategies. For example, to promote vertical evacuation, it may be useful to emphasize information about safety, such as building height. To promote horizontal evacuation, it may be useful to emphasize information that helps people to assess reachability, such as tsunami arrival time and lead-time. Since such information depends on each evacuee's location and situation, mobile devices and GPS offer significant potential for delivering personalized information. Particularly in spaces with high uncertainty, as represented by the Intermediate condition in the present study, providing objective spatiotemporal information plays a crucial role in correcting biases in individuals' subjective risk perception. However, because this study used a controlled VR environment, a more comprehensive analysis is needed before applying these findings to real-world environments.

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