

Article

Exploring the Educational Effects of a Point-Cloud-Derived 3D Urban Model on Residents' Spatial Understanding and Evacuation Behavioral Intentions for Sustainable Community-Based Tsunami Evacuation Education

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Abstract

This study explored the preliminary educational effects of a tsunami evacuation program using a streetscape reconstructed from a real district with a 3D laser scanner. The study area was Ono-machi, Kanazawa City, Japan, where 652 scan positions were captured using a Leica BLK360; the resulting point clouds were registered, cleaned, converted into a mesh model, and imported into Unity to build a desktop-based 3D evacuation experience. Twenty-five residents participated, operating the system individually or in small groups, discussing evacuation decisions, and completing pre- and post-experience questionnaires. Exploratory pre-post comparisons using the Wilcoxon signed-rank test were conducted for the 22 complete paired responses. Because five corresponding pairs were tested, the possibility of Type I error inflation due to multiple comparisons was considered. The results were interpreted using both uncorrected *p*-values and a Bonferroni-adjusted significance threshold of 0.01. The largest improvement was observed in the understanding of hazardous locations, with a mean increase of 1.59 points and a large effect size. The improvement in consideration of detours and alternative routes also remained below the adjusted threshold. Other corresponding item pairs showed positive descriptive changes and uncorrected *p*-values below 0.05, but they did not meet the Bonferroni-adjusted threshold. Therefore, these findings should be interpreted as preliminary evidence that a locally grounded, point-cloud-derived 3D urban model may support residents' place-based understanding of local hazards and evacuation-related reflection. By supporting local risk communication, preparedness, and evacuation-related reflection, this approach may contribute to sustainable community-based disaster-prevention education and the development of more resilient coastal communities.



Academic Editors: Jun Li, Shaowei Ning, Chengye Zhang and Yuanheng Sun

Received: 1 May 2026

Revised: 5 June 2026

Accepted: 18 June 2026

Published: 7 July 2026

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Keywords: desktop-based 3D evacuation experience; tsunami evacuation; point-cloud survey; spatial understanding; sustainable disaster-prevention education; community resilience

1. Introduction

Japan is one of the world's most seismically active countries and consequently faces an exceptionally high risk of earthquake-induced tsunami disasters. In particular, the Great East Japan Earthquake of 2011 caused more than 20,000 fatalities and missing persons due to the tsunami, and the scale of destruction shocked both Japan and the international community [1,2]. More recently, the 2024 Noto Peninsula Earthquake (Reiwa 6) recorded a maximum seismic intensity of 7 on the Japan Meteorological Agency (JMA) scale in Wajima City and Shika Town, Ishikawa Prefecture, resulting in more than 700 deaths (including indirect disaster-related deaths) [3]. In coastal areas, tsunamis occur on cycles ranging from several decades to once a century, and each event repeatedly produces severe human and material losses. Against this backdrop, tsunami disaster-prevention education is critically important.

Tsunami education must go beyond teaching the physical mechanisms of tsunami generation; it should foster “behavioral change” that enables individuals to protect their own lives. However, current disaster-prevention education often relies heavily on lecture-based, one-way information delivery, making it difficult for learners to engage actively. In many communities and municipalities, common approaches include confirming inundation zones using hazard maps, conducting field walks to identify hazardous locations, and checking evacuation routes and annotating them on maps. Yet these methods make it difficult for participants to form a concrete image of where inundation would actually reach when compared with the real landscape. To address such limitations, the application of Information and Communication Technology (ICT) and digital technologies in education has recently attracted increasing attention [4].

Among ICT-based disaster-prevention methods, technologies such as virtual reality (VR), augmented reality (AR), and geographic information systems (GIS) enable intuitive and experiential learning, contributing substantially to improved understanding and motivation. In tsunami education, which inherently involves spatial information, visually understanding local topography and evacuation routes is essential, and studies have highlighted the effectiveness of these technologies [5,6]. In this context, the use of 3D scanning, which can realistically reproduce real-world terrain and streetscapes—offers high practical value for educational settings. A 3D scanner captures the geometry of objects and terrain with high precision and generates three-dimensional digital models. Laser-based systems can acquire data at high accuracy and have been applied across diverse fields including architecture, medicine, and cultural heritage conservation. In recent years, portable 3D scanners have become available at price points that make them feasible for general educational use. They have also been used for post-disaster investigation; for example, following the 2011 disaster, tsunami height, inundation extent, and flow characteristics were mapped in detail using terrestrial laser scanning (TLS) from the rooftops of surviving buildings together with eyewitness video footage [7].

In tsunami disaster-prevention education, 3D scanning makes it possible to scan local terrain, buildings, and evacuation routes and reproduce them digitally. This allows learners to grasp, in an intuitive manner, elevation differences, building layouts, and the presence of visual and physical obstruction features that are difficult to capture through abstract maps or aerial photographs alone. Moreover, by using 3D maps and models derived from scan data to conduct interactive group learning and simulation-based workshops, educators can promote active and collaborative learning.

Experiential learning enables learners to acquire knowledge through action and observation; it is indispensable in domains such as disaster education, where effective “action” is ultimately required. Tsunami education using 3D scanning is therefore promising as a means of realizing dialogic and experiential learning. A sequence of learning activities—

scanning the community and examining evacuation scenarios—can strongly motivate participants and enhance their agency. By enabling participants to perceive disaster risks and evacuation realities as “real,” such approaches are expected to cultivate deeper risk awareness and stronger motivation to act. Additionally, dialogic implementation is known to make disaster-prevention education more effective by fostering participants’ ownership and initiative [8].

Based on this background, the aim of this study is to explore the preliminary educational effects of an experiential evacuation training program for local residents using a point-cloud-derived 3D model of an actual district. Using pre- and post-experience questionnaires, this study examines changes in residents’ perceived risk recognition, spatial understanding of hazardous locations and evacuation routes, self-efficacy, and evacuation-related behavioral intentions. The training includes not only tsunami inundation but also road blockages caused by building collapse and debris. Specifically, using pre- and post-experience questionnaires, we assess changes in: (1) risk perception, (2) spatial understanding of hazardous locations and evacuation routes, (3) self-efficacy, and (4) evacuation behavioral intentions. Furthermore, we analyze how perceived fidelity and trustworthiness of the measurement-based 3D model relates to learning outcomes and improved behavioral intentions, thereby examining how a measurement-based 3D model can be used in resident-focused disaster-prevention education.

The overarching significance of this study lies in advancing the potential of digital technologies in disaster education and establishing an educational method that cultivates the capabilities needed to protect lives. National policies also emphasize disaster-prevention education that promotes voluntary and proactive engagement [9] and note expectations for education that leverages advanced technologies [10]. To foster the ability to act autonomously during disasters, it is necessary to provide more effective learning environments in everyday contexts. By using 3D scanning to systematize knowledge acquisition, it becomes possible to ensure active learning, achieve place-based experiential learning, and deliver disaster education that is retained as durable knowledge.

This study has three key features: (1) it realizes education aligned with national educational policies; (2) it provides an engaging learning environment that helps participants sustain attention and maintain engagement; and (3) it enables experiences that approximate real disaster conditions through the proposed disaster-prevention education approach.

From the perspective of sustainability, fostering disaster-resilient communities is an integral part of sustainable development, as emphasized by Sustainable Development Goal 11 (Sustainable Cities and Communities). A point-cloud-derived 3D urban model offers a reusable, low-cost, and transferable educational asset that can be repeatedly used and shared across communities, supporting the long-term continuity of locally grounded disaster-prevention education. By strengthening residents’ place-based risk awareness and self-directed evacuation capacity, this approach contributes to the social sustainability and long-term resilience of coastal communities.

2. Review of Related Studies

2.1. Research on Tsunami Evacuation Drills

A substantial body of review and empirical research has examined evacuation drills. Terumoto conducted a disaster-prevention drill that assumed post-earthquake conditions to explore the potential and challenges of practical disaster training [11]. Togawa et al. reported cases in which tsunami evacuation drills were reflected in actual evacuation behavior and emphasized the importance of drills [12]. Aini et al. evaluated evacuation routes and formulated a tsunami emergency response plan for coastal communities [13]. Sato et al. argued that drills without pre-designated shelters can promote active learning

effects [14]. Other studies have suggested that integrated activities combining tsunami evacuation and disaster education can reduce tsunami damage [15] and have proposed training methods to enhance older adults' awareness of and engagement with disaster preparedness [16]. In addition, crowd evacuation modeling for tsunami evacuation has also been developed and examined [17,18].

2.2. ICT-Enabled Disaster Education

VR, AR, and mixed reality (MR) can serve as effective means to innovate educational methods by updating learning materials and enhancing learners' comprehension and engagement [19,20]. Mitsuhashi et al. argued that evacuation drills should be more realistic and developed a VR-based evacuation training system that incorporates game elements while remaining a fully self-contained system [21]. Tablet-based disaster education has also been reported [22]. A number of studies have examined evacuation routes and route planning in disaster scenarios [23–25]. Murokawa et al. developed a virtual evacuation drill system using Google Street View with the aim of conducting safe ICT-based training that is not affected by weather or other external conditions [26]. Robb et al. noted that whole-body, embodied experiences in learning physical concepts can foster positive learning attitudes [27]. Katada et al. developed a comprehensive tsunami disaster scenario simulation as a tool for tsunami disaster education [28]. Although many previous studies have focused on immersive head-mounted display (HMD) VR, the present study adopts a desktop-based interactive 3D simulation. Therefore, the system should not be interpreted as an immersive VR system in the strict sense. Rather, it is positioned as a monitor-based evacuation learning environment that uses a high-fidelity point-cloud-derived urban model.

2.3. Applications of 3D Scanning, LiDAR (Light Detection and Ranging), and Visualization Technologies

3D laser scanning offers considerable value for post-disaster forensic investigation, including detailed deformation measurement, virtual site reconstruction, and the creation of digital records for a wide range of purposes. At the same time, several challenges have been identified—such as equipment constraints, large data volumes, substantial processing times, and environmental conditions (e.g., scan range and weather) [29,30]. Laser scanning has proven effective for capturing post-disaster conditions, and a growing number of studies have investigated post-disaster surveys using LiDAR [31]. Furthermore, the continued use of laser scanning in post-disaster investigations has been argued to encourage improvements in numerical models by enabling the understanding of subtle behaviors that conventional models could not capture [32]. Pellenz et al. collected multimodal data using 3D laser scanning, GPS, IMU, and cameras, and demonstrated an ICP (Iterative Closest Point)-based 3D mapping approach suitable for real-time processing. Using terrain classification algorithms, they identified traversable terrain and obstacles, confirming effectiveness even in debris-strewn and highly uneven environments [33]. Verykokou et al. emphasized the importance of establishing an appropriate workflow in advance for rapid and reliable image-based 3D modeling to prepare for emergency response situations such as disaster management [34]. Simultaneous Localization and Mapping (SLAM) technology enables high-speed, high-resolution point cloud acquisition both outdoors and indoors, and is designed to operate without targets (markers). These emerging sensors are expected to enhance 3D scanning capabilities, streamline data acquisition and registration, and improve productivity [35].

In the cultural heritage domain, 3D laser scanners have been extensively used for the conservation and restoration of historic buildings and sites, digital archiving, and the assessment of deterioration states [36–41]. Numerous studies have also addressed laser scanning of complex forms in forest environments, including comparisons of point clouds

obtained from mobile laser scanning (MLS) and terrestrial laser scanning (TLS) [42,43]. More broadly, 3D digital tools have been developed as planning support tools for over two decades [44], and research has explored rapid measurement technologies for generating 3D city models [45,46]. 3D visualization has been used to inform the public and stakeholders and to raise awareness of various phenomena that affect planning areas and living environments [47–49]. However, despite the important contribution of VR to collaboration among practitioners, immersive VR has been reported to face difficulties in integrating with three-dimensional data and workflows [50].

In contrast to the above domains, research that applies terrestrial 3D laser scanning to disaster prevention and community-based urban planning remains limited. Several factors are likely to contribute to this gap. First, disaster prevention and urban planning often require coverage of wide areas; thus, approaches based on airborne LiDAR, satellite data, and GIS—i.e., regional-scale datasets—have been the mainstream, and the use of terrestrial 3D laser scanners has been comparatively constrained. Second, point cloud datasets are extremely large and require advanced expertise and considerable time for processing and analysis, which has limited adoption in practical disaster-related applications.

Nevertheless, there are many situations in which terrestrial 3D laser scanning can be highly effective in disaster prevention and urban planning practice. Even today, it is used for precise inspections of aging infrastructure and for detailed geometric surveys of hazardous slopes and levees that pose collapse risks. Looking ahead, these technologies could also be applied to refine evacuation routing and improve the spatial precision of hazard maps. By transferring accumulated techniques and knowledge from the cultural heritage domain to disaster management and urban planning, and by promoting cross-disciplinary collaboration, broader research and practical applications are expected. The potential of 3D laser scanning in disaster-resilient community planning therefore constitutes an important research area that has not yet been fully explored.

3. Materials and Methods

3.1. Study Area Selection

A tsunami-prone study area was selected to examine the effectiveness of a point-cloud-based 3D evacuation experience. We chose Ono-machi in Kanazawa City, Ishikawa Prefecture, Japan (Figure 1). Ono-machi is located along the Sea of Japan coast and has historically developed as a port town. During the Kaga Domain era, it prospered as a stopover port for Kitamae-bune trading ships, and today the area remains active in fisheries, seafood processing, and tourism, sustaining valuable local resources and a well-established community.



Figure 1. Ono-machi, Kanazawa City, Ishikawa Prefecture, Japan.

At the same time, Ono-machi faces risks typical of low-lying coastal districts, including potential tsunami impacts triggered by large earthquakes. In recent years, seismic

activity around the Noto Peninsula and adjacent offshore areas has drawn increasing attention, highlighting the need to strengthen tsunami disaster-prevention measures along the Ishikawa coastline. The district contains dense residential neighborhoods along the shoreline, and port and fishing facilities that support the local economy. While the town center preserves a historic streetscape that attracts many visitors, evacuation planning is challenged by narrow streets and complex local topography, which may constrain safe and efficient evacuation during a tsunami event.

3.2. Point-Cloud Survey Using a 3D Scanner

Surveying the entirety of Ono-machi would generate extremely large point-cloud datasets and could substantially hinder subsequent processing. Therefore, rather than attempting full coverage, we limited the survey extent to a practical area. The selected area encompasses the tsunami inundation assumption zone [51] and the routes to the designated evacuation site(s), while also including adjacent streets so that alternative evacuation paths can be considered.

Point clouds were acquired using a terrestrial laser scanner (Leica BLK360; Leica Geosystems AG, Heerbrugg, Switzerland). The BLK360 is widely used across multiple domains due to its lightweight design, high mobility, and user-friendly operation, making it particularly suitable for rapid data capture in the field and for surveys in constrained spaces. The resulting point-cloud data can be integrated with diverse applications such as VR and BIM, enabling digital-twin construction and advanced analyses. The BLK360 has been applied in many contexts, including digital documentation and exhibition of cultural heritage, creation of digital sets for media production, improving the efficiency of surveying workflows, and construction-site applications; comparative evaluations against other devices have also been reported [52,53].

For data acquisition, the scanner was placed at locations that did not obstruct vehicles or pedestrians, and scanning was initiated from each station. After completing a scan at one station, the team moved approximately 3 m to the next station and repeated the process until the target area was covered (Figure 2). An iPad was used to control the scanner and to verify the scanning status at each station during the survey. Four BLK360 units and four iPads were prepared, and surveys were conducted by a team of three to four people. Field campaigns were carried out eight times between July and August 2025, resulting in a total of 652 scan stations.



Figure 2. Field scene of the point-cloud survey (Leica BLK360 scanning procedure).

3.3. Point-Cloud Registration, Noise Removal, and 3D Meshing

To visualize the streetscape with high geometric fidelity, the acquired point clouds were processed through registration (integration), noise removal, and conversion to a 3D

mesh. The Leica Cyclone software (version 2025.0.0) suite was used for this workflow: Leica Cyclone FIELD 360 [54], Leica Cyclone REGISTER 360 [55], and Leica Cyclone 3DR [56]. Because point-cloud processing is computationally intensive, a high-performance workstation was required; the PC specifications used in this study are summarized in Table 1.

Table 1. Workstation specifications used for point-cloud processing.

Component	Specification
CPU	AMD Ryzen 7 9700X
Memory	64 GB (32 GB $\times$ 2, DDR5-5600)
Storage (M.2 SSD)	2 TB NVMe SSD (PCIe Gen4 $\times$ 4)
Graphics	NVIDIA GeForce RTX 5080 (16 GB)

First, the point-cloud data captured with the Leica BLK360 were imported into Leica Cyclone FIELD 360 (Figure 3). As the scans are initially displayed around their respective acquisition locations, small lateral misalignments may occur during field capture. To minimize such misalignment, Leica Cyclone FIELD 360 installed on the iPad was used to check scan connectivity on site and to make incremental adjustments so that adjacent scans overlapped consistently.

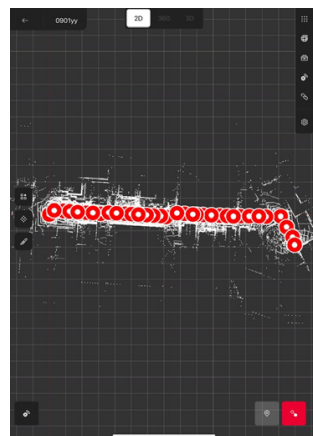


Figure 3. Leica Cyclone REGISTER 360 (registration workflow interface).

Next, Leica Cyclone REGISTER 360 was used to integrate the point clouds from all scan stations (Figure 4). This process—referred to as *registration*—aligns individual scans into a unified coordinate space based on shared targets (e.g., spherical markers or planar targets) and/or geometric feature correspondences. The bundle error was 0.009 m, the overlap was 45%, and the strength was 55%.

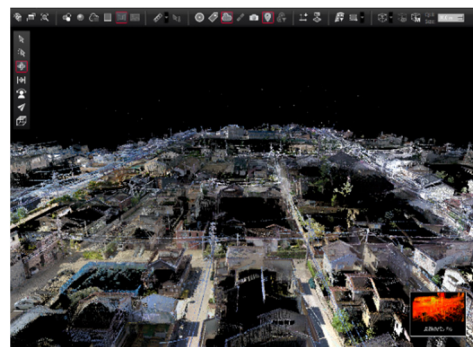


Figure 4. Point-cloud dataset in Leica Cyclone REGISTER 360 (integrated point clouds after registration).

In Leica Cyclone REGISTER 360, multiple scans are grouped as *links* and jointly optimized through a bundle adjustment, which simultaneously corrects scan positions and orientations across the dataset. A critical factor for robust alignment is *overlap*: the greater the shared area between adjacent scans, the more stable the automatic matching becomes.

Two complementary registration strategies can be used in combination: (1) target-based registration (e.g., spherical targets and checkerboards) and (2) cloud-to-cloud registration, which aligns scans by matching geometric features within the point clouds. In target-based workflows, identical targets detected in each scan are associated using the Match Targets function; incorrect correspondences can be removed and reassigned manually as needed. Overlap quality is internally quantified (e.g., by the number of shared points and match ratios between neighboring scans) and can be inspected through link colors and registration quality indicators within the software.

In Leica Cyclone 3DR, the workflow begins by importing the registered point-cloud data generated in Cyclone REGISTER 360 via [Import], and confirming the coordinate system and units before placing the dataset in the project (Figure 5). Next, performing a CloudWorx project conversion reorganizes the point cloud into a structure that is easier to link with CAD workflows, allowing lightweight referencing while preserving station information as well as intensity and color attributes. After conversion, outliers and artifacts are removed using [Cleaning] tools: isolated points, dynamic-object contamination, and reflective noise are filtered out; irrelevant areas are clipped; and, where necessary, thinning and/or density normalization is applied. Surface generation is performed using [Surface Modeling] → Scan to Mesh, in which surface normals are estimated and the point cloud is triangulated to generate polygonal faces. Finally, the model is exported as OBJ/FBX for downstream use. Once noise removal is complete, the processed model is exported in obj format.

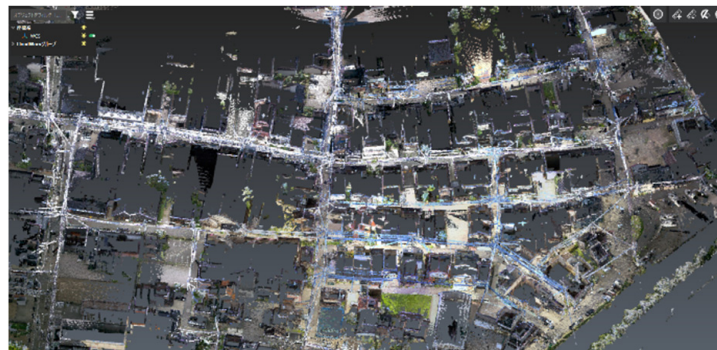


Figure 5. Leica Cyclone 3DR (point-cloud cleaning and Scan-to-Mesh workflow).

After registration, consistency was evaluated using residual errors and link-quality indicators. When links exceeded the acceptance threshold, we examined potential causes—insufficient overlap at the relevant station, contamination by moving objects, and/or incorrect target correspondences—and iteratively refined the dataset by disabling the problematic link, re-registering the affected scans, and re-optimizing the bundle adjustment until global accuracy stabilized. In addition, scan alignment was visually inspected from multiple viewpoints (e.g., top and side views) to verify overlap and to confirm that no double images were present in linear features such as building façades and guardrails. Finally, the integrated point cloud was exported in a format that preserves essential attributes (color and intensity) and scale, in preparation for downstream processing in Cyclone 3DR (noise removal and meshing) and subsequent import into Unity (2022.3.36f1). Through this workflow, we generated a highly accurate, measurement-based integrated point-cloud dataset

reflecting the real environment and established a 3D simulation-ready virtual setting as the foundation for tsunami disaster-prevention education.

3.4. Simulation Development: Import into Unity, Fluid Configuration, and Walk-Through Setup

The 3D streetscape model exported in obj format was imported into the Unity Editor by placing the file in the Assets folder. After import, the model scale and materials were adjusted and verified to ensure correct visualization and spatial consistency within Unity.

Tsunami inundation behavior was reproduced in Unity using Zibra Liquid. After installing the package, a Zibra Liquid object was added to the scene, and a Liquid Container (bounding box) defining the simulation domain was positioned to cover the target area. The container size was tuned to the minimum necessary extent that included the building blocks, roads, and river corridor. In this study, the purpose of these models is not to reproduce engineering-accurate hydrodynamic or structural responses, but to convey key qualitative features relevant to evacuation decision-making (e.g., spatial extent of inundation).

To generate the inflow representing tsunami intrusion, an Emitter was added and configured by specifying the outlet position, orientation, and discharge rate. For tsunami-like phenomena in which water volume rises rapidly within a short period, a time-varying discharge profile provides a more realistic representation than a constant-rate inflow.

For collision handling, colliders were assigned to the terrain and building meshes and registered as Zibra Colliders/Manipulators, enabling the flow to interact with the environment and be blocked by walls and other obstacles (Figure 6). Through these settings, we constructed an experiential learning environment in which participants can intuitively understand tsunami approach direction, inundation extent, and flow behavior on a realistic streetscape derived from point-cloud measurements. The inundation scenario was configured with reference to the Kanazawa City published tsunami inundation assumption zone (Figure 7). The Zibra Liquid simulation was not designed as a physically calibrated hydrodynamic model. The purpose of the inundation representation was educational visualization, namely to help participants recognize the approximate spatial extent and direction of tsunami inundation in relation to the published tsunami inundation assumption zone. Therefore, parameters such as flow velocity, discharge volume, arrival time, and water depth should not be interpreted as engineering predictions.

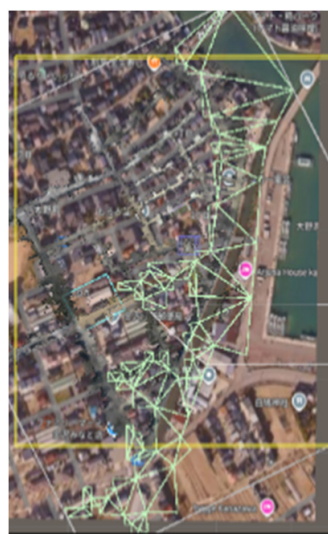


Figure 6. Tsunami inundation simulation in Unity.

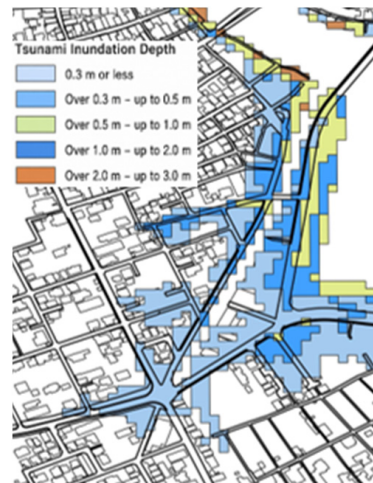


Figure 7. Tsunami inundation assumption area (Kanazawa City).

To compare how the presence of tsunami inundation influences evacuation decision-making, we implemented two experimental conditions—“tsunami” and “no-tsunami”—within the same Unity scene using the Zibra Liquid-based fluid model (Figures 8 and 9). In the tsunami condition, participants were able to visually understand the expected inundation extent based on the published tsunami inundation assumption zone.

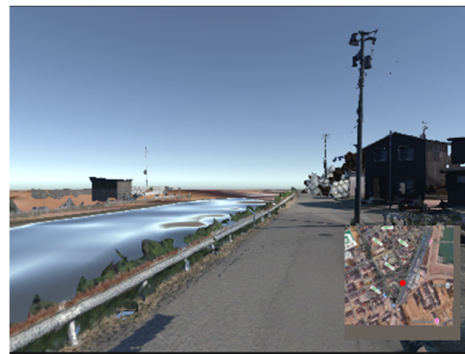


Figure 8. “No-tsunami” condition (without inundation).

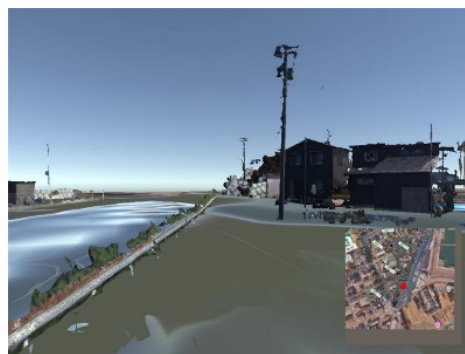


Figure 9. “Tsunami” condition (with inundation).

During the experience, participants could switch between conditions by pressing the Enter key, enabling immediate, within-location comparisons of perception and route-choice behavior under inundated versus non-inundated circumstances. This implementation provided an experimental platform for evaluating the effects of inundation information on spatial understanding, risk perception, and the consideration of alternative routes, in combination with verbal protocols, behavioral logs, and questionnaire-based measures.

We configured the fluid scenario to account for river run-up, which is a critical mechanism in real tsunami events, rather than assuming uniform inland inundation from the shoreline. By driving the inflow along the river channel, the simulation allows the wave to penetrate inland and enables users to visually recognize possible changes in inundation movement and apparent water-level conditions around bridges and channel constrictions. For the walk-through configuration, we implemented custom scripts developed in Visual Studio (2022) and imported them into Unity. The scripts were written in C# and placed in the Assets/Scripts directory. To provide intuitive movement control, JoyToKey (v7.3) was used to map controller inputs to keyboard commands for navigation. Because the point-cloud-derived streetscape model contains small height irregularities, we developed an additional script to stabilize the user viewpoint by keeping the camera (and thus the user's perceived eye height) constant during movement.

To reproduce building collapse and enable learners to perceive changes in accessibility that directly affect evacuation behavior, we introduced a physics-based destruction representation in Unity. Using RayFire (1.80), collapse was not treated as a uniform fragmentation process; instead, buildings were decomposed into components such as the roof, exterior walls (including the structural frame/columns). We assigned different polygon subdivision densities and fracture patterns to each component to reflect differences in material and structural behavior (Figure 10). For example, roof elements were modeled to produce relatively large fragments that tend to fall and accumulate, whereas regions around windows were modeled to fragment into smaller pieces. This approach avoided monotonous debris fields and allowed the simulation to reproduce evacuation-relevant environmental changes after collapse, including localized road blockages, reduced effective street width, and loss of visibility (Figures 11 and 12).



Figure 10. Physics-based building collapse and debris generation in Unity (RayFire).

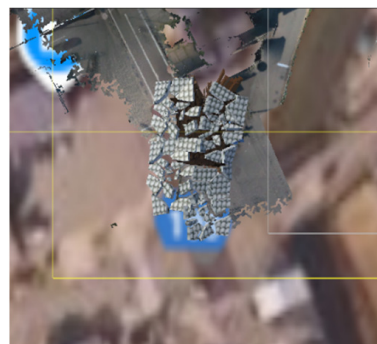


Figure 11. Top-down view of debris accumulation and the resulting road blockage.



Figure 12. Street-level view of evacuation-route obstruction caused by collapse-induced debris.

In practice, fracture settings were adjusted as follows: columns used Splinters to encourage vertical cracking with a lower Amount; and the main building body used Voronoi with a higher Amount to increase fragmentation complexity.

While RayFire provides physically based destruction, real-time fracture simulation is computationally demanding. When executed concurrently with a point-cloud-derived urban block model, it can cause substantial framerate drops, thereby disrupting the continuity of the experiential learning process. To address this issue, we pre-recorded (cached) the collapse animation using Unity’s recording/cache functionality and adopted a playback-based approach in which the recorded motion is triggered at runtime by a “start playback” event. This method ensures both reproducibility (i.e., identical collapse behavior under the same condition) and stable performance, making the system more suitable for deployment in educational settings.

In addition, collapse representation should not be limited to enhancing visual realism; it must be explicitly linked to the learning objectives of evacuation planning. Accordingly, we defined approximately five locations within the district where collapse-induced route obstruction could occur, where residents would be expected to consider alternative routes. At these locations, debris accumulation and collapsed structural elements alter the passable space, requiring participants to make decisions based on an assumed “impassable” state—such as detouring, connecting to higher ground, and maintaining safe visibility.

To prevent learning loss caused by participants becoming disoriented in the 3D environment, we continuously displayed an aerial-photo-based minimap (overview map) in the lower-right corner of the screen (Figure 13). Although the point-cloud-based streetscape closely resembles the real environment, first-time users may find it difficult to grasp the overall spatial structure when the viewpoint is fixed at street level, which can shift exploratory behavior toward resolving “getting lost” rather than learning evacuation strategies. The minimap therefore provides an overview reference that supports both local (walk-through) and global (district-scale) spatial cognition simultaneously. The participant’s position is shown as a red marker that follows movement in real time, facilitating identification of current location and understanding of the relative relationship to the destination (distance and direction). This reduces cognitive load devoted to spatial orientation and enables participants to allocate attention to the intended learning task evacuation decision-making and alternative route planning based on inundation extent and collapse locations. Moreover, aerial imagery intuitively conveys building layout and road geometry and functions as a paper-map-like reference frame, which may also connect naturally to residents’ existing spatial memory. In this way, the minimap contributes not only to usability but also to more effective information presentation that supports situational awareness and decision-making processes during disasters.



Figure 13. Aerial-photo minimap with real-time user-position marker and directional guidance cues.

To support participants' understanding of evacuation behavior, we placed visual guidance elements in the simulation, including pictograms indicating the evacuation shelter and arrows indicating evacuation direction [57] (Figures 14–16). These elements were designed with reference to the national framework for disaster-prevention signs and symbols and were adopted as standardized representations that can be interpreted intuitively by a wide range of users. Standardization of signage helps reduce variability in interpretation attributable to differences in age or local familiarity, thereby contributing to shorter search times and faster decision-making in emergency contexts. In addition, by presenting directional information within the user's field of view, the system supports wayfinding even when route changes are required due to inundation or collapse-related blockages. This encourages participants to consider alternative routes and promotes learning that emphasizes proactive, self-directed evacuation decision-making.



Figure 14. Evacuation-shelter pictogram.



Figure 15. Directional arrow indicator for evacuation guidance.



Figure 16. Example of guidance signage displayed in the 3D streetscape.

3.5. Experiment: Experience with the Developed Simulation

Before the experience, participants were informed that the inundation and collapse representations were intended for educational visualization and should not be interpreted as engineering predictions of actual tsunami flow velocity, water depth, arrival time, or structural failure processes. The simulation was designed to support recognition of the approximate inundation area, possible obstruction points, and the need to consider alternative routes, rather than to teach physically calibrated tsunami behavior.

The experience was implemented as a desktop-based 3D simulation rather than an HMD-based VR system. Participants viewed the reconstructed urban environment on a PC monitor and navigated the scene using a controller. Accordingly, the system differs from immersive VR in terms of field of view, embodied perception, and motion-sickness risk. The training session was conducted on 29 March 2026. To emphasize discussion and collaborative reflection, participants took part individually or in small groups of two to four. When participants took part in groups, one participant operated the controller while the group discussed evacuation decisions and carried out the tsunami evacuation training (Figure 17). The training used a Unity-built application exported from the development environment. When the application was launched, the scenario began automatically with an audio announcement stating that a tsunami had occurred and instructing participants to start evacuating. Movement was controlled with the controller's stick input, enabling participants to navigate the desktop-based 3D streetscape with intuitive camera control.



Figure 17. Photograph of the tsunami evacuation training session.

The evacuation starting point was set near Kanazawa Port, with an explicit focus on helping participants understand the spatial extent of the predicted tsunami inundation area. After confirming the inundation zone, participants initiated evacuation toward the designated shelter, Ono-machi Elementary School (Figure 18). During navigation, participants were instructed to avoid entering inundated areas. In addition, because

building collapse is a plausible hazard during tsunami evacuation, several buildings were intentionally collapsed within the simulation to create road blockages, requiring participants to detour rather than follow the shortest route. The training ended when participants arrived at the elementary school after exploring several possible routes.

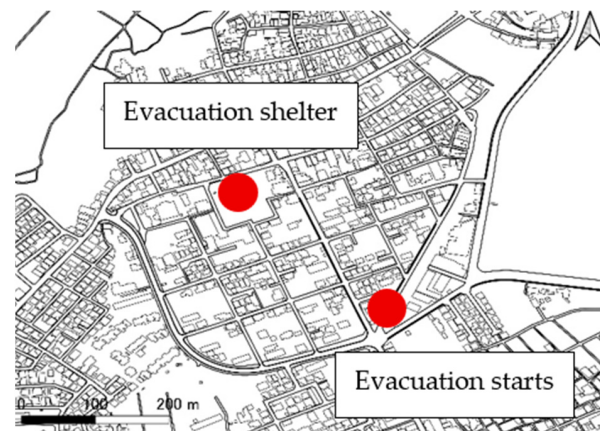


Figure 18. Evacuation starting point and designated shelter (Ono-machi Elementary School).

A key feature of this training is that it enables participants to intuitively understand characteristics that are difficult to grasp through conventional two-dimensional materials such as paper maps—for example, street narrowness—through embodied movement in a 3D environment. In particular, by introducing dynamic obstacles such as road closures caused by building collapse, participants were required to make situational, adaptive decisions rather than simply memorizing a fixed route. To examine how this experience contributed to the personalization of risk awareness (i.e., making it feel personally relevant), we analyze responses from a post-experience questionnaire.

Questionnaire surveys were administered before and after the training experience. All questionnaire items were rated on a five-point Likert scale, with higher scores indicating stronger agreement or more positive evaluations. Missing responses were excluded on an item-by-item basis; therefore, the number of valid responses differed across items. Free-response comments were reviewed and categorized thematically by the authors to summarize major themes related to hazard recognition, behavioral intention, safety, and requests for improvement.

3.6. Questionnaire Design and Statistical Analysis

The questionnaire items were developed based on the learning objectives of the program and prior studies on tsunami evacuation education, disaster-prevention learning, and ICT-based educational environments. The items were designed to measure perceived hazard recognition, spatial understanding, self-efficacy, usability, perceived realism and reliability of the 3D model, behavioral intention, and factors promoting learning. To ensure content validity, the questionnaire was reviewed by the authors, including researchers with expertise in disaster prevention, urban planning, and 3D visualization.

Because the items used five-point Likert scales and only a limited number of complete pairs were available, we examined pre-post changes with the Wilcoxon signed-rank test for conceptually corresponding item pairs, and computed effect sizes as $r = Z / \sqrt{N}$. Since the same five corresponding item pairs were compared, multiple testing could increase the risk of Type I error inflation. Therefore, we applied a Bonferroni-adjusted significance threshold of $\alpha = 0.01$ in addition to reporting the uncorrected p -values. We treated these analyses as exploratory, given the small sample and the fact that some pre- and post-experience items corresponded conceptually rather than being identical.

We also computed Cronbach's alpha for each multi-item construct. Given the small sample, we read these coefficients as supplementary indicators rather than as definitive evidence of scale reliability.

4. Results

Twenty-five residents participated in the experience. The demographic characteristics, residential background, and prior disaster-prevention experience of the participants are summarized in Table 2. Of these, 23 completed the pre-experience survey, 24 completed the post-experience survey, and 22 provided complete pre/post pairs. The exploratory pre-post statistical analysis was conducted using the 22 complete paired responses. For item pairs with missing post-experience responses, the number of valid pairs was adjusted accordingly. One participant discontinued after the pre-survey, and two participants joined the session after the pre-survey had been administered and therefore provided post-experience responses only. Demographic distributions reported below are based on all 25 participants, including non-responses with valid demographic data. Participants in their 50s and 70s accounted for the largest proportions, with seven participants in each group (28% each), followed by those in their 40s and 80s, with four participants in each group (16% each). Participants in their 60s represented the smallest group, with two participants (8%). Overall, the participants were predominantly middle-aged and older adults, particularly those in their 50s to 70s, suggesting that many of the participants were local residents with a relatively high level of awareness of disaster prevention.

Table 2. Demographic characteristics, residential background, and prior disaster-prevention experience of participants.

Item	Category	Response	<i>n</i>	Percentage (%)
A1	Age group	40s	4	16
		50s	7	28
		60s	2	8
		70s	7	28
		80s	4	16
		No response	1	4
A2	Length of residence	6–10 years	2	8
		11–20 years	2	8
		21 years or longer	20	80
		No response	1	4
B1	Participation in disaster prevention drills over the past four years	0 times	6	24
		1 time	4	16
		2 times	2	8
		3 times or more	12	48
		No response	1	4
B2	Awareness of hazard maps	Never seen one	4	16
		Have seen one	17	68
		Understand the contents	3	12
		No response	1	4
B3	Experience participating in disaster prevention education	Yes	16	64
		No	8	32
		No response	1	4
C	Experience with 3D/VR technologies	None	15	60
		Some experience	8	32
		Frequent experience	0	0
		No response	2	8

The majority of participants had seen a hazard map (68%); however, only 12.0% reported that they understood its contents. This finding suggests that, while hazard maps were relatively familiar to participants, many had not developed a sufficiently deep understanding of the information presented in them.

Regarding prior experience with disaster prevention education, including lectures, study sessions, and hands-on events, 16 participants answered “yes” (64%), whereas eight answered “no” (32%); one participant did not respond. Although more than half of the par-

ticipants had previously participated in some form of disaster prevention education, their participation in the present experience suggests a need for alternative learning approaches that go beyond conventional paper-based materials and lecture-style instruction.

In terms of prior experience with 3D models, VR, games, or related technologies, 15 participants reported no experience (60%), eight reported limited experience (32%), and no participants reported frequent experience; two participants did not respond. This result indicates that most participants were unfamiliar with 3D/VR technologies and that, for many, the present program may have been their first experience with desktop-based 3D disaster-prevention learning.

4.1. Pre-Experience Perceptions (D Items, $N = 23$)

Table 3 presents the descriptive statistics for the six items related to disaster prevention knowledge and confidence measured before the experience using a five-point Likert scale ($N = 23$). In particular, D1, which measured participants' awareness of hazardous locations, showed the lowest mean score ($M = 2.65$). This suggests that participants did not have a sufficient understanding of specific hazardous locations within their own living areas. Although D4, which measured self-efficacy, showed the 2nd highest mean score among the six items ($M = 3.00$), it remained at the midpoint of the scale. Therefore, participants' confidence in their ability to take appropriate evacuation actions was not sufficiently high before the experience.

Table 3. Pre-experience perceptions: D items.

Item	Question Item	N	Mean	SD	Min.	Max.
D1	I think I can specifically explain hazardous locations, such as areas at risk of inundation or building collapse.	23	2.65	1.03	1	5
D2	I think I can consider evacuation routes while assuming impassable roads and possible detours.	23	3.09	1.12	1	5
D3	I think I can explain the criteria for deciding when to evacuate immediately.	23	2.91	1.08	1	5
D4	I am confident that I can take action when an actual disaster occurs.	23	3.00	1.00	1	4
D5	I have discussed evacuation with my family members and neighbors.	23	2.91	1.12	1	4
D6	I sufficiently understand evacuation and disaster risks using only paper maps or hazard maps.	23	2.70	0.93	1	4

4.2. Perceptions of Disaster Prevention Learning (E Items, $N = 23$)

Table 4 shows the descriptive statistics for the E items, which assessed participants' awareness and self-evaluated abilities regarding disaster prevention learning before the experience. E1, representing a locally grounded risk awareness, showed a relatively high mean score ($M = 3.83$), whereas E4, representing the clarity of evacuation timing, showed the lowest mean score ($M = 3.00$).

Table 4. Perceptions of disaster prevention learning (E items).

Item	Question Item	N	Mean	SD	Min.	Max.
E1	I think I can regard disasters as personally relevant.	23	3.83	1.03	2	5
E2	I think I can visualize disaster risks in a concrete manner.	23	3.43	0.95	2	5
E3	I think I can consider alternative evacuation routes in the event of a disaster.	23	3.43	1.04	2	5
E4	I clearly understand when to start evacuation.	23	3.00	0.85	1	4

These findings suggest that participants already tended to regard disasters as personally relevant before the experience. However, the criteria for determining when to initiate evacuation remained unclear. This indicates a potential gap between general disaster awareness and the ability to make concrete evacuation decisions.

4.3. Post-Experience Learning Effects (F Items, $N = 22\text{--}24$)

Table 5 presents the descriptive statistics for the F items, which measured the learning effects after the experience. The number of valid responses ranged from 22 to 24 across the items because of missing responses and one discontinued case.

Table 5. Post-experience learning effects (F items).

Item	Question Item	N	Mean	SD	Min.	Max.
F1	I was able to concretely understand hazardous locations, such as areas at risk of inundation or building collapse, as well as narrow roads.	24	4.29	1.00	1	5
F2	I can explain the rationale for choosing specific evacuation routes.	24	3.92	1.10	1	5
F3	I developed a perspective for considering detour routes or alternative evacuation routes.	24	4.08	0.93	1	5
F4	The timing for starting evacuation became clearer to me.	24	3.67	1.17	1	5
F5	I was able to organize the key points that should be communicated to my family members and neighbors.	22	3.82	0.96	1	5

F1, which assessed participants' understanding of hazardous locations, showed the highest mean score ($M = 4.29$). This suggests that the 3D model was particularly effective in helping participants visually recognize hazardous locations. Although F4, which assessed the clarification of evacuation timing, showed the lowest mean score among the F items ($M = 3.67$), it still increased by 0.76 points compared with the corresponding pre-experience item D3 ($M = 2.91$).

4.4. Changes in Conceptually Corresponding Pre- and Post-Experience Items

An exploratory pre–post comparison was conducted using the complete paired responses (Table 6). Because the questionnaire items were measured on five-point Likert scales and the sample size was limited, the Wilcoxon signed-rank test was used. We conducted a descriptive comparison between pre-experience items and conceptually corresponding post-experience items.

Table 6. Exploratory pre–post comparison of corresponding items.

Pair	Construct	N	Mean Difference	Wilcoxon p -Value	Effect Size r
D1–F1	Understanding of hazardous locations	22	+1.591	$p < 0.001$	0.718
D2–F2	Explanation of route-choice rationale	22	+0.773	0.0133	0.528
D2–F3	Consideration of detours and alternative routes	22	+0.955	0.0082	0.564
D3–F4	Clarity of evacuation timing	22	+0.682	0.0357	0.448
D5–F5	Communication with family members and neighbors	21	+0.952	0.0132	0.541

Note. Because five corresponding item pairs were tested, multiple comparisons could increase the risk of Type I error inflation. Therefore, a Bonferroni-adjusted significance threshold of 0.01 was considered in addition to the uncorrected p -values. Under this adjusted threshold, D1–F1 and D2–F3 remained statistically significant, whereas D2–F2, D3–F4, and D5–F5 should be interpreted as positive descriptive trends rather than statistically significant improvements after correction.

This descriptive trend suggests that the experiential learning program using the 3D model may have helped participants recognize and understand hazardous locations more concretely.

The largest improvement was observed for D1–F1, which assessed the understanding of hazardous locations, with a mean increase of 1.591 points, $p < 0.001$, and an effect size of $r = 0.718$. These results indicate that the experience helped participants identify local hazardous locations more clearly and reflect on possible evacuation routes. However, because the sample size was small and the item pairs were conceptually corresponding rather than identical, these results should be interpreted as exploratory.

We report the Cronbach's alpha values in Table 7 only as a rough reference. With 22–24 valid responses per item group, these coefficients can vary considerably, so we do not treat them as firm evidence of scale reliability. They are included only to give a

supplementary sense of response consistency, and confirming the reliability of these scales will require larger samples.

Table 7. Internal consistency of questionnaire constructs.

Construct	Items	N	Cronbach's Alpha
Pre-experience disaster-prevention knowledge and confidence	D1–D6	23	0.854
Pre-experience disaster-prevention learning perceptions	E1–E4	23	0.703
Post-experience learning effects	F1–F5	22	0.941
Evaluation of the 3D model	G1–G8	24	0.897
Usability and experience quality	H1–H7	24	0.782
Behavioral intention	I1–I5	24	0.776
Learning-promoting factors	J1–J6	23	0.851
Core learning-promoting factors	J1–J3	23	0.767

4.5. Evaluation of the 3D Model (G Items, N = 24)

Table 8 presents the evaluation results for the eight items related to the reproducibility, reliability, and educational usefulness of the 3D laser scanner-derived model.

Table 8. Evaluation of the 3D Model Derived from 3D Laser Scanner Data (G Items).

Item	Question Item	N	Mean	SD	Min.	Max.
G1	Buildings, roads, and rivers were reproduced in a way that closely matched the actual impression of the site.	24	4.33	0.64	3	5
G2	The model made it easier to understand elevation differences and steps, and to judge potential hazards.	24	3.88	0.90	2	5
G3	The model helped me understand road width, visibility, and corners, and imagine risks during movement.	24	4.00	0.78	2	5
G4	This 3D model made actual evacuation behavior more concrete than paper maps.	24	4.58	0.72	2	5
G5	Knowing that the model was based on measurement data increased my trust in the content.	24	4.58	0.72	2	5
G6	There were few locations in the measurement-based model that felt unnatural.	24	4.17	0.92	2	5
G7	I think the realism of buildings and roads provides useful information for evacuation decision-making.	24	4.54	0.72	2	5
G8	The representations of inundation and building collapse felt close to reality.	24	4.17	0.87	2	5

Among the items, G4, which assessed whether the 3D model could make evacuation behavior more concrete than paper maps, and G5, which assessed the sense of reliability derived from the fact that the model was based on measurement data, both showed the highest mean scores ($M = 4.58$). These results suggest that the measurement-based streetscape model was perceived as concrete and useful for imagining evacuation situations.

Although G2, which assessed the understanding of terrain and elevation differences, showed a slightly lower mean score ($M = 3.88$), this may reflect the local characteristics of the study area, where steep topographical changes are relatively limited.

Although G8 received a relatively high score, this result should be interpreted carefully. A high perceived realism score does not indicate that the inundation and collapse simulations were physically accurate. Rather, it suggests that participants perceived the visual scenario as concrete and useful for imagining evacuation situations. To avoid overconfidence or misunderstanding, educational implementations of this system should explicitly explain that the simulated water movement, water depth, flow velocity, arrival time, and collapse behavior are simplified visual representations and not objective predictions of actual disaster dynamics.

4.6. Usability, Behavioral Intention, and Factors Promoting Learning

The score for ease of operation, H1 ($M = 3.67$), was lower than those of the other items, suggesting that controller operation may have placed a burden on older participants (Table 9).

Table 9. Key results for usability, behavioral intention, and factors promoting learning.

Category	Item	N	Mean	SD	Min.	Max.
H: Usability and experience quality	H1. The operation was easy to understand.	24	3.67	1.05	2	5
H: Usability and experience quality	H6. I would recommend this experience to others.	24	4.50	0.59	3	5
I: Behavioral intention	I4. I would like to participate in local disaster prevention drills.	24	4.46	0.51	4	5
I: Behavioral intention	I5. I would like to consider mutual assistance with neighbors.	24	4.63	0.49	4	5
J: Factors promoting learning	J1. I was able to regard the disaster as personally relevant.	23	4.65	0.49	4	5
J: Factors promoting learning	J2. I was able to visualize the hazard concretely.	23	4.57	0.59	3	5
J: Factors promoting learning	J3. The experiential format helped my understanding.	23	4.57	0.51	4	5

The intention to consider mutual assistance with neighbors, I5 ($M = 4.63$), and the intention to participate in local disaster prevention drills, I4 ($M = 4.46$), received especially high evaluations.

Among these items, J1, which assessed whether participants were able to regard the disaster as personally relevant, showed the highest mean score ($M = 4.65$).

These results indicate that the experience was not merely perceived as easy to understand but was associated with the formation of behavioral intentions and a sense of personal relevance among participants.

4.7. Safety and Summary of Free-Response Comments

Regarding discomfort associated with the desktop-based 3D experience, 23 of 25 participants (two responses were missing, 92.0%) reported no discomfort; among valid responses, all 23 reported no discomfort (Table 10). No participants reported severe discomfort. Although some variation was observed among participants, the overall score was not excessively high.

Table 10. Summary of safety and free-response comments.

Category	Main Findings	Representative Comments	Implications
Safety	92.0% reported no discomfort	No severe interruption was observed.	The system appears feasible for implementation, even among middle-aged and older local residents.
Awareness of hazardous locations	Participants mentioned riverside areas, impassable roads, old buildings, and steps.	"Areas near the river"; "Places with many old buildings may become impassable even if they are nearby."	Participants were able to understand hazardous locations in relation to specific local contexts.
Post-experience behavioral intention	Participants mentioned confirming evacuation routes, holding family discussions, and reviewing preparedness.	"I want to confirm evacuation routes"; "I want to hold a family discussion"; "I want to review how to evacuate."	The learning experience was connected to practical actions within households and the community.
Requests for improvement	Participants requested operational support, improved model representation, and expansion of the experience area.	"Controller operation is difficult for older adults"; "I would like to experience a wider area."	There is room for improvement in interface design and scenario representation.

These results suggest that the system can be implemented as an educational tool for local residents while maintaining a high sense of realism and ensuring an acceptable level of safety.

In the free-response comments, participants mentioned hazardous locations such as riverside areas, impassable roads, and areas with many old buildings. As actions

they wished to take after the experience, many participants referred to confirming evacuation routes, discussing evacuation with family members, and reviewing disaster preparedness measures.

On the other hand, participants also suggested several areas for improvement, including enhanced operational support, more detailed visual and scenario representations, and the expansion of the experience area to better reflect local conditions.

5. Discussion

The exploratory statistical analysis partially supported the descriptive findings. The largest and most robust improvement was observed in the D1–F1 pair, which assessed participants' understanding of hazardous locations. In addition, the D2–F3 pair, which was related to the consideration of detours and alternative routes, remained statistically significant after applying the Bonferroni-adjusted threshold. Other corresponding pairs showed positive descriptive changes, but they should be interpreted as exploratory trends because they did not remain statistically significant after adjustment for multiple comparisons. These findings suggest that the point-cloud-derived 3D urban model may be particularly effective in helping residents transform abstract hazard awareness into concrete, place-based recognition, while its effects on broader behavioral intentions require further validation with larger samples.

One of the clearest descriptive findings was the reported improvement in participants' understanding of hazardous locations. In the descriptive comparison between conceptually corresponding pre- and post-experience items, the D1–F1 pair showed the largest increase (+1.59), suggesting that the real-space visualization provided by the 3D model helped participants connect general tsunami-risk information with familiar streets and evacuation routes, such as “areas around one's own home” and “roads actually used for evacuation.”

In particular, multiple comments in the free-response section referred to riverside areas and impassable locations. This indicates that participants did not merely form a general impression of risk but developed a place-based understanding of hazards.

The relatively high scores for F2 and F3 also suggest that participants did more than memorize routes; they also considered why a route should be selected and how to change routes when roads became impassable. This effect can be interpreted as resulting from the integrated presentation of road width, visibility, the sense of enclosure created by buildings, and the presence of obstacles within a walking-perspective 3D environment, environmental elements that are difficult to fully grasp from two-dimensional paper maps.

In contrast, although clarification of evacuation timing improved from D3 to F4, the degree of improvement was smaller than that observed for other items. This may be because the decision of when to start evacuation depends not only on spatial information but also on the integration of multiple factors, such as warnings, surrounding conditions, family composition, and time of day. Therefore, the 3D model alone may not have been sufficient to fully support this type of temporal decision-making.

This result suggests that while the 3D model was effective in supporting participants' understanding of “where hazards are located” and “which routes should be used,” additional information is needed to support decisions regarding “when to act.” Future improvements may include time-series representations of inundation progression and available evacuation time, integration with warning information, and the presentation of multiple evacuation scenarios.

In the G items, both the superiority over paper maps (G4) and the sense of reliability based on measurement data (G5) showed high mean scores of 4.58. This indicates that the educational value of the 3D laser scanner-derived model was not limited to its visual realism. Rather, the fact that the model was based on actual measurements may have

functioned as information that supported the validity and reliability of the learning content for participants.

In this survey, 80% of the participants had lived in the area for 21 years or longer. The fact that these long-term residents, who were highly familiar with the local environment, evaluated the model as being close to the actual impression of the site is particularly meaningful. This finding suggests that both measurement accuracy and local specificity are important for enhancing the persuasiveness of educational content.

Although the overall evaluation of the H items was high, it is important to note that H1, “The operation was easy to understand,” remained at 3.67. Many participants were unfamiliar with 3D/VR experiences, and the free-response comments included statements such as “I did not know how to operate it” and “Controller operation is difficult for older adults.” This suggests a limitation in directly applying game-like interfaces to the main target population of disaster prevention education.

However, the intention to recommend the experience to others (H6) was high, with a mean score of 4.50. This suggests that although participants experienced some operational difficulties, they strongly recognized the value of the experience itself. Therefore, future improvements should focus less on changing the direction of the content itself and more on optimizing operational support and user guidance for older adults and beginners.

The scores for behavioral intention, represented by the I items, were generally high. In particular, items related to community-oriented behavior, such as the intention to consider mutual assistance with neighbors and to participate in local disaster prevention drills, received relatively high evaluations. These responses indicate that the experience encouraged participants to think beyond their own evacuation and consider mutual assistance and local drills.

Furthermore, the frequent references in the free-response comments to family discussions and route confirmation indicate that the experience was not limited to learning during the session itself. Rather, the experience appears to have prompted some participants to discuss evacuation with family members and to check routes in the actual town. This suggests that experiential disaster prevention education contributes to disseminate knowledge and awareness from individual participants to their families and neighboring residents.

Among the J items, “I was able to regard the disaster as personally relevant” received the highest evaluation. Participants also highly evaluated the ability to visualize hazards concretely and the effectiveness of the experiential learning format. Entering a 3D model that reproduced their own living environment and confirming evacuation routes and hazardous locations within it appears to have transformed disaster prevention from a general issue into a more immediate and personal concern.

This effect can be understood as a form of learning based on local specificity, which is difficult to achieve using generic CG models or fictional urban environments. In other words, the value of the 3D model lies not only in its precise reproduction of reality but also in its ability to evoke a locally grounded risk awareness by connecting the learning experience with participants’ own memories and everyday experiences.

From the perspective of safety, discomfort associated with the desktop-based 3D experience was rarely observed, suggesting that the system has a high level of feasibility for implementation in disaster prevention education for local residents.

This result may indicate that a certain level of tension contributed to the sense of realism and learning effect. At the same time, it also suggests that future implementation will require difficulty adjustment and support systems according to participant characteristics, particularly when the program is introduced to broader groups of residents.

This study examined a desktop-based tsunami evacuation learning program that uses a point-cloud-derived streetscape. While many studies have employed VR for disaster

education, research that constructs highly realistic 3D models has also been reported [58–60]. However, these efforts often remain at the level of passive viewing (e.g., watching videos), whereas the present approach combines a 3D environment with collaborative learning, which likely increased participants' engagement and willingness to participate actively. Given that interactive discussion has been shown to enhance educational effectiveness [8], the present results support the effectiveness of such an approach for tsunami disaster education as well. The findings of this study should be interpreted primarily as evidence of educational and cognitive effects rather than as evidence of evacuation optimization. The system was designed to support residents' place-based hazard recognition, evacuation-related reflection, and behavioral intentions through interaction with a locally reconstructed 3D environment. Therefore, the primary contribution of this study is not the development of an evacuation-route optimization algorithm, but the design and exploratory evaluation of an experiential learning environment that helps residents understand local hazards and reflect on evacuation decisions. Nevertheless, the point-cloud-derived urban model contributes to support more advanced spatial analyses. Future work should integrate GIS-based network analysis or pathfinding algorithms to compare residents' selected routes with computationally derived optimal or safer routes. Such an approach would make it possible to evaluate not only subjective changes in hazard recognition and behavioral intention, but also the relationship between participants' route-choice behavior and spatially optimized evacuation routes.

Although unmanned aerial vehicle (UAV) photogrammetry can efficiently cover wider areas and is useful for macroscopic route identification, terrestrial laser scanning was selected in this study because the educational objective required street-level geometric fidelity. In particular, road width, visibility at corners, the sense of enclosure created by buildings, steps, and potential blockage points are experienced from the pedestrian perspective and are difficult to reproduce sufficiently using aerial data alone. Therefore, the value of TLS in this study lies not in wide-area efficiency but in its ability to reproduce evacuation-relevant street-level spatial conditions. Future implementations should consider a hybrid workflow that combines UAV photogrammetry for wide-area modeling with TLS for critical street-level segments, such as narrow roads, intersections, riverfront areas, and evacuation bottlenecks. Future work should also explicitly integrate flood-prone zones, road-blockage points, and possible detour routes as spatial layers within the 3D model and link them to GIS-based route analysis. This would allow the system to present not only an experiential visualization of inundation but also a more analytically grounded comparison between predicted hazard zones, evacuation routes, and participant route choices. This study has several limitations. First, the sample size was limited to 25 participants, and only 22 participants provided complete pre–post paired responses. Therefore, the findings should not be interpreted as statistically generalizable to all coastal communities. Rather, this study should be regarded as an exploratory community-based case study that provides preliminary evidence regarding the educational potential of point-cloud-derived 3D urban models. In addition, the study relied primarily on self-reported questionnaire responses; therefore, future studies should incorporate larger samples, control or comparison groups, validated questionnaire scales, and behavioral or spatial-log data.

The design itself was a single-group pre–post comparison without a control group, so we cannot fully rule out confounding factors such as Hawthorne, history, or maturation effects. In particular, the study cannot conclusively demonstrate the incremental educational benefit of the point-cloud-derived 3D model compared with conventional paper maps, hazard maps, or generic CG-based models. Accordingly, the findings should be interpreted as preliminary evidence of perceived educational effects, rather than as causal evidence of superiority over other media. Future studies should employ controlled designs, such

as comparisons with paper-map-based training or generic 3D/CG models, to clarify the unique contribution of locally measured point-cloud-derived models. Participant age and digital literacy are a second concern. The participants in this study were middle-aged and older local residents, and no participants under 40 years of age were included. Because the system uses a desktop-based 3D environment and controller-based operation, digital literacy and prior experience with 3D interfaces may influence usability, perceived realism, and learning outcomes. The relatively lower score for ease of operation may therefore reflect, at least in part, the age composition of the sample rather than the usability of the system alone. Consequently, the findings should not be generalized to younger populations or digitally experienced users without further investigation. Future studies should include younger participants, students, and users with diverse levels of digital literacy to examine how age and prior experience affect learning effects and operability. Finally, the tsunami inundation and building-collapse representations were not physically calibrated. The Zibra Liquid (2.1.5) simulation was used to visualize the approximate spatial extent and direction of inundation based on the published tsunami inundation assumption zone, but parameters such as water depth, flow velocity, discharge volume, and arrival time were not validated against hydrodynamic simulation results or observed tsunami data. Therefore, the system should not be used to teach precise physical tsunami behavior or engineering-level risk prediction. In future implementations, the simulation should be combined with clear instructional warnings, hazard-map information, and, where possible, validated hydrodynamic models to reduce the risk that participants misinterpret simplified visual effects as accurate physical laws.

6. Conclusions

This study explored the preliminary educational effects of tsunami evacuation education using a highly realistic streetscape reconstructed from 3D laser scanning of a real town. The target area was Ono-machi, Kanazawa City, Ishikawa Prefecture (Japan). The area spanning from the predicted inundation zone to the designated shelter was scanned using a Leica BLK360 at 652 scan positions (four devices operated; eight survey campaigns conducted in July–August 2025). The point clouds were registered, cleaned, and converted into a meshed 3D model, and then imported into Unity. Within the simulation, Zibra Liquid was used to enable switching between “tsunami” and “no-tsunami” conditions within the same scene, allowing participants to compare the spatial extent of inundation and corresponding changes in route accessibility.

The experiment was conducted in March 2026. Participants operated the system while engaging in discussion and completed pre- and post-experience questionnaires. The 3D model was also highly evaluated for its ability to make evacuation behavior more concrete than paper maps and for the high level of trust generated by its basis in measurement data. Furthermore, the experience appeared to support the formation of behavioral intentions and a sense of personal relevance, encouraging subsequent actions closely related to everyday disaster preparedness, such as discussing evacuation with family members and confirming evacuation routes. This study provides preliminary evidence that a desktop-based 3D evacuation experience using a point-cloud-derived urban model may support local residents’ concrete recognition of hazardous locations and encourage evacuation-related reflection. The most robust improvement was found in the understanding of hazardous locations, and positive descriptive changes were also observed in other evacuation-related domains. Still, the results call for caution: the sample was small, the participants were all middle-aged or older, and the multiple-comparison adjustment left only a few robust findings. Future work will need larger and more age-diverse samples, participants with varying digital literacy, and validated hydrodynamic or hazard information to strengthen both the educational

effect and the accuracy of risk communication. With further improvements, particularly in usability and temporal scenario presentation, the system has the potential to be more widely implemented in real-world disaster prevention education. A limitation of this study is that some roof structures could not be fully captured through terrestrial laser scanning. Future work should consider integrating aerial imagery or UAV-based photogrammetry to complement the terrestrial point-cloud data and improve the completeness of the 3D urban model. Overall, by providing a potentially reusable and transferable digital platform for community-based disaster-prevention education, this approach may support sustainable disaster risk reduction and the long-term resilience of coastal communities, aligning with Sustainable Development Goal 11 (Sustainable Cities and Communities).

Author Contributions: Conceptualization, Y.Y.; methodology, Y.Y.; software, T.X.; validation, D.-T.N., T.-M.-T.N., N.A. and P.T.; formal analysis, Y.Y. and A.M.; investigation, Y.Y. and A.M.; resources, Y.Y.; writing—original draft preparation, Y.Y.; writing—review and editing, T.X., D.-T.N., T.-M.-T.N., N.A. and P.T.; visualization, D.-T.N. and T.-M.-T.N.; supervision, T.X.; project administration, Y.Y.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Japan Society for the Promotion of Science (JSPS) KAKENHI, grant number 25K00847.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the National Institute of Technology, Ishikawa College (Approval No. REC2025-05, approved on 31 January 2026).

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

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions related to participant responses.

Acknowledgments: The authors would like to thank the residents who participated in this study and all individuals who supported the field survey and training sessions.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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