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Article

Metaverse-Based Evacuation Training: Design, Implementation, and Experiment Focusing on Earthquake Evacuation

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Abstract: Virtual reality (VR) can realize evacuation training in an immersive, interactive, safe, three-dimensional virtual world. Many VR-based evacuation training systems have been developed; however, they typically notify participants explicitly or implicitly before the evacuation training; thus, participants are mentally ready for successful evacuation. To satisfy a prerequisite where participants do not have mental readiness, this study proposes a prototype of a metaverse-based evacuation training system called "Metavearthquake". The main characteristic of the proposed prototype system is that evacuation training begins unexpectedly due to a sudden earthquake in the metaverse (virtual world); participants are then required to evacuate to a safe place while making decisions under difficult earthquake-caused situations. The prototype system introduces scenarios and nonplayable characters to express difficult situations that may occur after an earthquake occurrence. To heighten training effects, the prototype system supports reflection (reflection-on-action) by replaying the evacuation of participants. An experiment implied that a sudden earthquake is indispensable for realistic simulated evacuation experiences. In summary, Metavearthquake is a metaverse-based evacuation training system that provides realistic simulated earthquake evacuation experiences in terms of evacuation behaviors, emotions, and training effects.

Keywords: evacuation training; metaverse; earthquake; simulated evacuation experiences; decision making; virtual reality; virtual world; nonplayable characters; reflection

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1. Introduction

Natural and man-made disasters can cause catastrophic damage and transform our daily lives. In particular, we are vulnerable to unpredictable (sudden) disasters such as earthquakes and terrorist attacks. To survive an unpredictable disaster, we may need to quickly evacuate to a safe place (e.g., shelter). At the very least, successful evacuation necessitates knowledge of evacuation routes, and evacuation training helps meet this role requirement. However, in conventional evacuation training, participants simply follow and memorize recommended evacuation routes. In other words, realistic simulated evacuation experiences are not provided. During the evacuation process in actual disasters, we frequently encounter challenging situations and make difficult decisions while hoping for the best result. For example, when a recommended evacuation route is inaccessible, we must choose another route or when an injured person asks for help, we must decide whether to rescue the person. For example, when a recommended evacuation route is inaccessible, we must choose another route, or when an injured person asks for help, we must decide whether to rescue the person. Decision making is more difficult under life-threatening circumstances, such as approaching flames. For successful evacuation, we need to not only know evacuation routes but also be able to make quick and confident decisions in difficult disaster-caused situations.

New evacuation training needs to express disaster-caused situations realistically and make participants feel as if they were in an actual disaster situation. However, realistic expression of disaster-caused situations in the real world may increase physical risks for participants (i.e., injury and death). For example, building fire evacuation training occasionally uses nontoxic smoke but can hardly use real flame because of participant safety. Thus, real-world evacuation training has a realism dilemma. One approach to solving this dilemma is to use digital technology for the expression. For example, a location-based evacuation training game uses digital content (e.g., video and multiple-choice questions) to express possible disaster-caused situations at a player's current location [1] and heighten the realism by introducing augmented reality as additional digital content [2]. However, even if the expression method is replaced with digital technology, the physical risks do not disappear completely because participants move around the real world. Therefore, to ensure participant safety, virtual-world evacuation training is needed. In other words, virtual reality (VR) can be employed for evacuation training.

In recent years, VR has rapidly spread into society while providing high realism (immersiveness and interactiveness) through VR headsets and controllers. VR has been actively applied to safety training [3], and VR-based evacuation training systems that can realistically express disaster-caused situations in three-dimensional (3D) virtual worlds and provide simulated evacuation experiences have been developed [4]. Most VR-based evacuation training systems notify participants explicitly or implicitly that evacuation training will begin in due course, and participants prepare mentally for successful evacuation. In other words, it is difficult to simulate the decision making process under their mentally tough circumstances (e.g., panic and stupefaction), and participants may not be able to utilize training effects in real evacuation. Therefore, it is desirable for VR-based evacuation training systems (especially for unpredictable disasters) to satisfy a prerequisite where participants do not have such mental readiness. To meet this requirement, the author focused on the metaverse as social VR, where a user can access a virtual world as an avatar and communicate with other users.

The metaverse has attracted significant attention in various fields, including education [5–8]. The definitions of the metaverse are diverse [9–13], and the requirements (or functions) for the users' comfortable, fruitful activities in virtual worlds have not yet been fully established. For example, the metaverse can be defined in terms of environment, interface, interaction, and social value and can be realized not only as VR but also as AR [9]. In the field of education, although the definition is being clarified, including artificial intelligence perspectives [14] and the fusion of virtual and real worlds [15], the metaverse has been emphasized in terms of its potential rather than its definition. It is actively applied to or investigated in domains such as language learning [16], STEM (Science, Technology, Engineering, and Mathematics) education [17], teacher education [18], university education [19], and gifted education [20]. In the field of disaster risk reduction, the metaverse has been used as a platform for evacuee behavior simulation [21], wayfinding data collection [22], collaborative sharing of flood knowledge [23], and firefighter training [24]. However, the use of the metaverse for practical evacuation training has not yet been significant. The author's group proposed the concept of evacuation training in the metaverse (ETM), wherein a disaster suddenly occurs and users are asked to evacuate in a 3D virtual world [25]. In other words, ETM simulates unpredictable disasters that suddenly change normal time (NT) to emergency time (ET). Based on ETM, a metaverse-based evacuation training system focusing on earthquake evacuation, "Metavearthquake", has been prototyped, which offers the original university metaverse service, "Tokudiverse", for Tokushima University. This metaverse service enables users (i.e., students and faculty members) to communicate via avatars as if they are in the real campus. The prototyped metaverse-based evacuation training system aims to provide realistic, effective simulated evacuation training by not only simulating sudden earthquakes but also implementing a realistic 3D virtual world, which contains scenario-based expressions of earthquake-caused situations, nonplayable character-based evacuee expressions, and reflection-on-action support.

This study aims to position Metavearthquake as a new type of evacuation training system and present methodologies for its design, implementation, and experimentation. A proof-of-concept and experimental research approach is used in this study.

The remainder of this article is organized as follows. Section 2 briefly presents VR-based evacuation training systems and related work from a wider point of view. Section 3 describes the implementation of Metavearthquake, demonstrating an evacuation training model. Section 4 describes the implementation of Metavearthquake, illustrating its architecture and user interfaces. Section 5 reports on an experiment where three groups are required to evacuate due to a sudden earthquake in Tokudiverse. Original acronyms (abbreviations) in this article are given in Appendix A.

2. Literature Review

Owing to the frequent occurrence of disasters globally, many VR-based evacuation training systems that provide immersive, interactive, and safe 3D virtual worlds have been developed; these systems offer realistic simulated evacuation experiences entailing decision making in disaster-caused situations. Many VR-based evacuation training systems have demonstrated positive training effects compared with conventional methods (e.g., video-based instruction). Furthermore, VR-based evacuation training systems tend to adopt gaming elements. VR has been applied to various disasters not only for evacuation training but also for evacuation-related topics. This literature review briefly presents VR-based evacuation training systems and related work, expanding the focus to risk visualization, emergency responses, evacuee behavior analysis, etc.

2.1. Earthquake

Earthquakes are a typical unpredictable disaster and are targeted in many VR-based evacuation training systems. Lovreglio et al. developed a series of immersive VR serious games (IVRSGs) that simulate building earthquakes in a hospital and enable trainees (hospital staff and visitors) to learn earthquake preparedness [26–28]. These IVRSGs have provided many thought-provoking results and have had a significant impact on Metavearthquake. For example, the hospital was 3D-modeled faithfully on the real hospital, and nonplayable characters (NPCs) were programmed to behave interactively. In addition, these IVRSGs emphasized training on how to make proper decisions in difficult situations that may happen in the hospital, enabling trainees to select presented options and reflect on their decisions through video and audio playback. A customizable IVRSG that aims to heighten the training effect by adapting training components (e.g., a storyline and teaching method) to each trainee has been developed [29]. Its extended version that supports reflection-in-action by providing immediate feedback (correct or incorrect, and instruction) regarding a trainee's decision making has also been developed [30]. Another IVRSG that has been developed adopts a spiral feedback method for reflection-in-action and promotes reflection-on-action by presenting a postgame assessment checklist [31].

VR can be used to visualize dangerous earthquake-caused situations and collect and analyze behavioral data in earthquake emergencies. Earthquake simulation VR systems visualize seismic physical damage (movements of indoor nonstructural components) through accurate physics calculations to enhance users' danger detection ability and earthquake preparedness [32,33]. An IVR system that not only visualizes seismic physical damage in a school but also emphasizes safe and dangerous areas from an educational point of view has been developed [34]. An investigation using an IVR system was performed regarding earthquake evacuation in a hospital and revealed phenomena such as the fact that many participants followed NPCs and did not make decisions by themselves [35].

2.2. Fire

In fires, we are occasionally given time to evacuate, depending on the situation. However, indoor fires frequently result in crowded evacuation which may prevent successful evacuation. Thus, VR-based evacuation training systems targeting fires have been actively developed. A VR-based evacuation training system that simulates a series of actions for fire evacuation (e.g., turning on the fire alarm) and prompts or corrects users to take action by presenting text-based situation explanations and feedback on incorrect decisions has been developed [36]. Another VR-based evacuation training system that focuses on hospital fires and adopts a cave automatic virtual environment to make evacuation training immersive has been developed [37]. An investigation using a VR-based evacuation training system that simulated not only building fires but also an active shooter incident reported that participants tended to complete evacuation by making decisions more smoothly in fire scenarios than in active shooting incident scenarios [38]. In indoor fires, responsible parties are required to guide occupants to safe spots and/or extinguish the fire. An IVR system targeting subway fires aimed at training station staff to guide passengers to safe spots by introducing interactive multiagent evacuees (model-based simulation) influenced by surroundings and guidance [39].

VR-based evacuation training systems targeting indoor fire evacuation should have 3D virtual worlds that are faithful to actual buildings and accurately simulate the phenomena of fire and smoke (spread) and evacuees (movement) to make simulated evacuation experiences more realistic. For example, a VR-based evacuation training system visualized smoke spread and crowd evacuation in a 3D building converted from building information modeling data using fluid dynamics and physical collision simulations [40]. A mobile VR-based evacuation training system that uses a light detection and ranging device to build a 3D virtual world that is faithful to a real building has been developed [41]. VR-based fire simulation systems where participants are forced to evacuate in virtual buildings have been used to collect and analyze participant behavior data [42,43]. The data contribute to clarifying evacuation phenomena and designing buildings proper for evacuation.

2.3. Other Disasters

Flooding is not necessarily an unpredictable disaster. Climate change has been causing devastating floods globally. A nonimmersive VRSG that provides simulated flood evacuation experiences based on various storylines in virtual urban areas has been developed [44]. An experiment using a VR application that visualized an overflowing river and evacuee movements examined how decision making about evacuation changed in different conditions [45].

Active shooter incidents are unpredictable human-made disasters that make evacuation complicated and difficult due to the criminal's mental confusion. VR systems that simulate active shooting incidents in virtual offices [46] and university [47] buildings and allow participants to take life-protecting decisions and actions (e.g., run, hide, and fight) have been developed. A collaborative VR system that realizes a multiplayer environment, including AI-based agents (NPCs), and provides multipurpose emergency training by occupant and security personnel modules has been developed [48].

3. Design

VR-based evacuation training systems have become considerably sophisticated owing to recent advances in VR technologies [3,4]. However, conventional systems do not necessarily provide participants with realistic simulated evacuation experiences in terms of a sudden (surprise) disaster, i.e., training for the decision making process under mentally challenging circumstances. Metavearthquake aims at overcoming this shortcoming and providing more realistic, effective simulated earthquake evacuation training than conventional systems.

A metaverse-based evacuation training system needs a metaverse that works as a comfortable world for users and does not make them foresee evacuation training. Thus, Metavearthquake typically exists behind Tokudiverse and is suddenly activated to generate an earthquake in a 3D virtual world. Only Tokudiverse users (TUs) who have begun to evacuate after Metavearthquake activation are regarded as Metavearthquake participants (MPs).

3.1. Requirements

Tokudiverse satisfies multiuser access and avatar communication (voice and gesture) as basic requirements for the metaverse, and Metavearthquake satisfies the following requirements. Figure 1 shows an overview of the requirements for Metavearthquake.

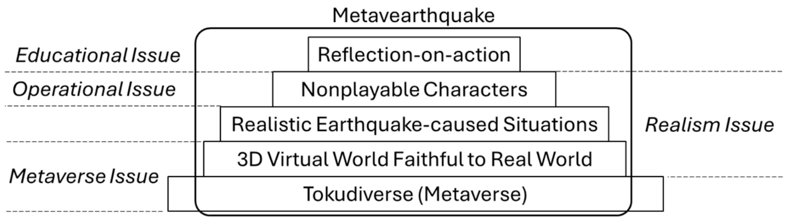


Figure 1. Requirements for Metavearthquake.

3.1.1. Three-Dimensional Virtual World Faithful to the Real World

In many cases, evacuation training is performed for participants to survive disasters in their living areas. Thus, a fictional virtual world does not fit Metavearthquake, and a 3D virtual world faithful to the real world should be constructed. In other words, Metavearthquake (Tokudiverse) should replicate the real university campus of Tokushima University in the virtual world and enable MPs to make decisions in realistic earthquake-caused situations. Many VR-based evacuation training systems capable of generating 3D virtual worlds faithful to the real world have been developed (e.g., [26,27,39,41]).

Many metaverse services allow users to adopt favorite avatars (e.g., imaginary characters) to establish their identities. In contrast, the avatars in Metavearthquake should visually resemble real students and faculty members as much as possible and not be allowed to perform unrealistic actions (e.g., flying and teleportation) so that MPs can empathize with each other via avatars and make realistic decisions. In addition, avatars should reflect MPs' physical characteristics. For example, if an MP has injured legs, it is recommended that the MP adopts an avatar with limited moving speed or an avatar seated in a wheelchair.

3.1.2. Realistic Earthquake-Caused Situations

Many VR-based evacuation training systems that express disaster-caused situations realistically using simulations have been developed. For example, furniture collapse [32,33], fire spread [39,40], and crowd movement [39,43] have been simulated and visualized. In the real world, unpredictable disasters likely cause difficult situations different from simulation results, and difficult disaster-caused situations entail difficult decision making. Thus, a customizable scenario is necessary to intentionally express difficult earthquake-caused situations, such as cases where MPs find a safer evacuation route in a space surrounded by debris but then realize that the route is a dead end. Metavearthquake adopts a scenario-based rather than a simulation-based expression of earthquake-caused situations. Each scenario describes when an earthquake occurs in the virtual world and what situations are caused.

3.1.3. Nonplayable Characters

The metaverse requires many users to function properly. A metaverse service with few simultaneous users will reduce the users' experience due to infrequent communication and consequently make the users leave. New metaverse services struggle with depopulation while devising ways to gather users and encourage frequent and long-term access. Metavearthquake is no exception and must avoid depopulation to express difficult human-caused situations (e.g., congestion and conformity bias). However, an effective way to avoid depopulation differs in each metaverse service. For example, a metaverse service for youths may actively introduce gaming elements. An effective way to avoid depopulation in Metavearthquake is to introduce NPCs. Many VR-based evacuation training systems have introduced interactive NPCs that can behave realistically during evacuation (e.g., [27,30,47]) Reasonable evacuation routes of NPCs (e.g., the shortest route from a current position to the nearest safe place) can be determined by multiagent simulations. For example, Dijkstra's algorithm has been used to express NPCs (evacuees) that avoid fires and move to a safe spot [39].

3.1.4. Reflection-on-Action

Conventional evacuation training frequently ends when participants reach a designated safe place. This style of evacuation training, even if providing realistic simulated evacuation experiences, may not maximize training effects because the participants do not reflect on their decision making and behaviors during evacuation. Reflection is an important activity to transform experience into concepts (or knowledge) and can be roughly divided into reflection-in-action and reflection-on-action [49]. Reflection-in-action involves people making or adjusting their immediate decisions (and/or actions) from their experiences and perceived surroundings during actions. Reflection-on-action involves people observing their entire decisions from their experiences and outcomes after a series of actions and generating concepts for better decisions. A VR-based evacuation training system focusing on reflection-in-action enables participants to reflect on their incorrect decision for a short time and retry decision making [30]. In a real evacuation, reflection-in-action is not always easy because quick decision making is successively required. Therefore, Metavearthquake does not consider reflection-in-action but provides MPs with the opportunity of reflection-on-action, i.e., holistically observing simulated evacuation experiences. For example, an MP who has evacuated slowly via the shortest but narrow route may reflect on his/her entire evacuation and notice that the evacuation should have been carried out more speedily via a wider route for safer evacuation.

3.2. Evacuation Training Model

Previously, the author proposed an evacuation training model for effective evacuation training [1,50], which consisted of four stages defined in Kolb's experiential learning model [51]. This model has been adapted to Metavearthquake by defining three phases: NT, ET, and reflection time (RT). Figure 2 illustrates the adapted evacuation training model.

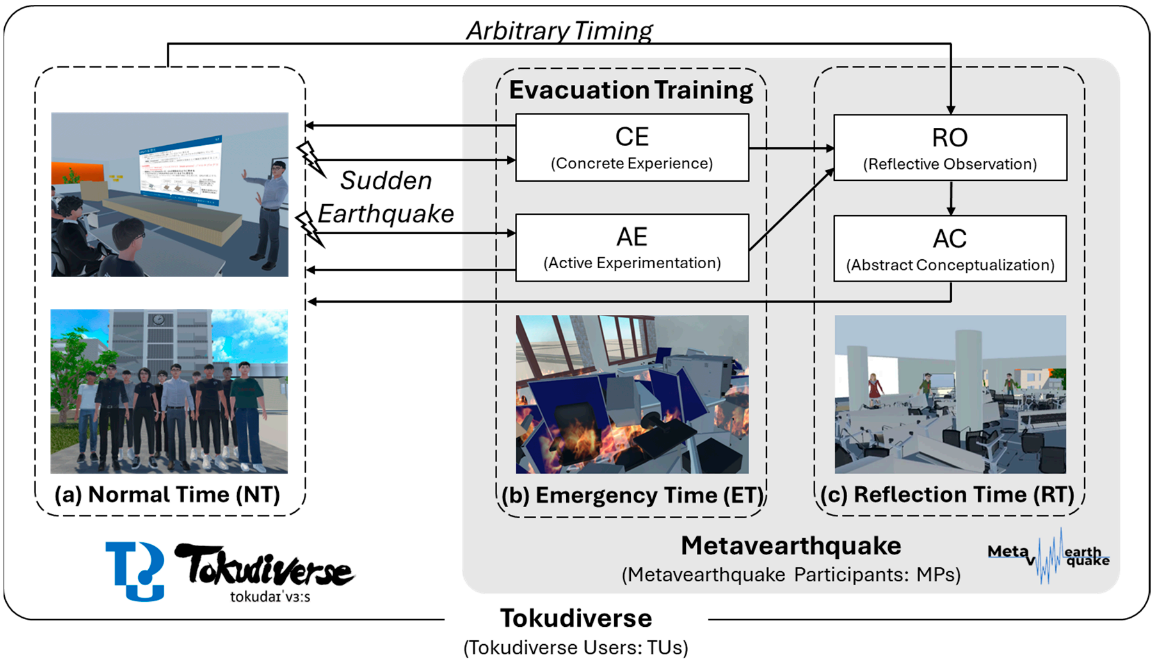


Figure 2. Evacuation training model adapted to Metavearthquake: (**a**) NT phase (avatars in a virtual university campus and a student MP's view in on-lecture); (**b**) ET phase (flames and scattered furniture as earthquake-caused situations); (**c**) RT phase (observing evacuation behaviors through replay).

3.2.1. Phase

The adapted model recommends repetitive transitions between the ET and RT phases. It is expected that following the model, MPs will properly transform simulated evacuation experiences into concepts and then refine these concepts. In addition, MPs will improve self-efficacy in successful evacuation, i.e., they will become able to make quick and confident decisions in the real evacuation by simply applying their refined concepts.

(1) Normal Time

This phase indicates a relatively long time before an earthquake occurs, i.e., when TUs are receiving Tokudiverse's services. For example, in this phase, a professor can deliver a slideshow-based lecture via his/her avatar, which can control a screen component in a lecture room.

(2) Emergency Time

This phase indicates a relatively short time during the shakes and after the shakes stop. In other words, this phase indicates that Metavearthquake is activated, and TUs are asked to evacuate to a safe place due to a sudden earthquake. In this phase, MPs are distinguished from TUs.

(3) Reflection Time

This phase is prepared to maximize training effects. MPs can arbitrarily transition to this phase during the NT phase; however, it is expected to occur following the ET phase.

3.2.2. Stage

The adapted model inherits the four stages of the previous model: concrete experience (CE), reflective observation (RO), abstract conceptualization (AC), and active experimentation (AE).

(1) Concrete Experience

This stage corresponds to the ET phase. It is up to TUs to decide whether to evacuate; i.e., evacuation is not mandatory. MPs are required to make decisions in difficult earthquake-caused situations encountered during evacuation. When reaching a safe place within a time limit, an MP is recognized as a successful evacuee. Beyond the time limit, TUs (including MPs) transition to the NT phase.

(2) Reflective Observation

Only determining the success or failure of an evacuation (i.e., time-dependent result) does not maximize training effects. In this stage, MPs reflect on their evacuation (decision making and behavior) to identify the factors of a successful or failed evacuation. For example, an MP who failed in evacuation by chasing the crowd reflects on the decision and identifies that passive decision making may have led to the failure.

(3) Abstract Conceptualization

In this stage, MPs formulate their concepts (e.g., rules for successful evacuation) based on their outcomes from the RO stage (i.e., identified factors of a successful or failed evacuation). For example, an MP (exemplified above) formulates a rule that quickly checking surroundings and autonomously selecting an evacuation path must be performed. The RO and AC stages can be performed simultaneously.

(4) Active Experimentation

This stage corresponds to the ET phase, where MPs apply their outcomes from the AC stage (i.e., formulated concepts) to evacuation training that entails the same or similar difficult earthquake-caused situations.

4. Implementation

Metavearthquake (and Tokudiverse) comprises VR and web server applications. The VR application works on a personal computer (PC) as the core component of Metavearthquake, supporting VR headsets with controllers (e.g., Meta Quest and HTC Vive). The web server application stores and processes TU data (e.g., logon ID and password).

4.1. Method

The VR application was implemented using a cross-platform game engine (Unity), a standard specification of extended/cross-reality technologies (OpenXR), and a network engine (Photon). OpenXR was used to ensure VR headset compatibility. Photon was used to realize multiuser access and avatar communication, and its services "Fusion" and "Voice" were used for object synchronization (e.g., avatar position and state) and real-time voice chat, respectively, in the mode of real-time host–client communication. At present, theoretically, 100 TUs can simultaneously access Tokudiverse at maximum. A Tokudiverse administrator activates the VR application (Tokudiverse) by assigning his/her PC as a host computer for a synchronized virtual world (referred to as "room" in Photon), and then TUs access the virtual world (i.e., Tokudiverse) via the host computer from their PCs (client computers). This method enables object synchronization among TUs via the host computer. The web server application was implemented as a Java servlet that accesses databases. Figure 3 shows the architecture of Metavearthquake. Figure 4 illustrates the characteristics of Metavearthquake.

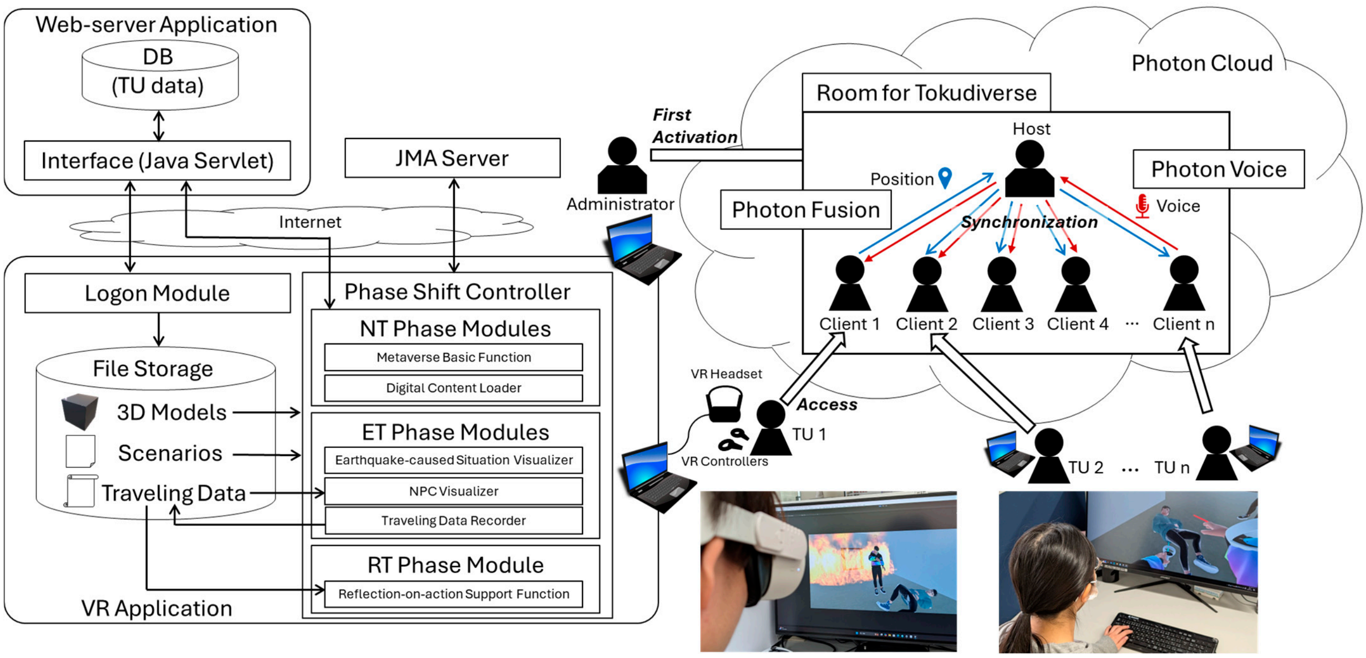


Figure 3. Metavearthquake architecture.

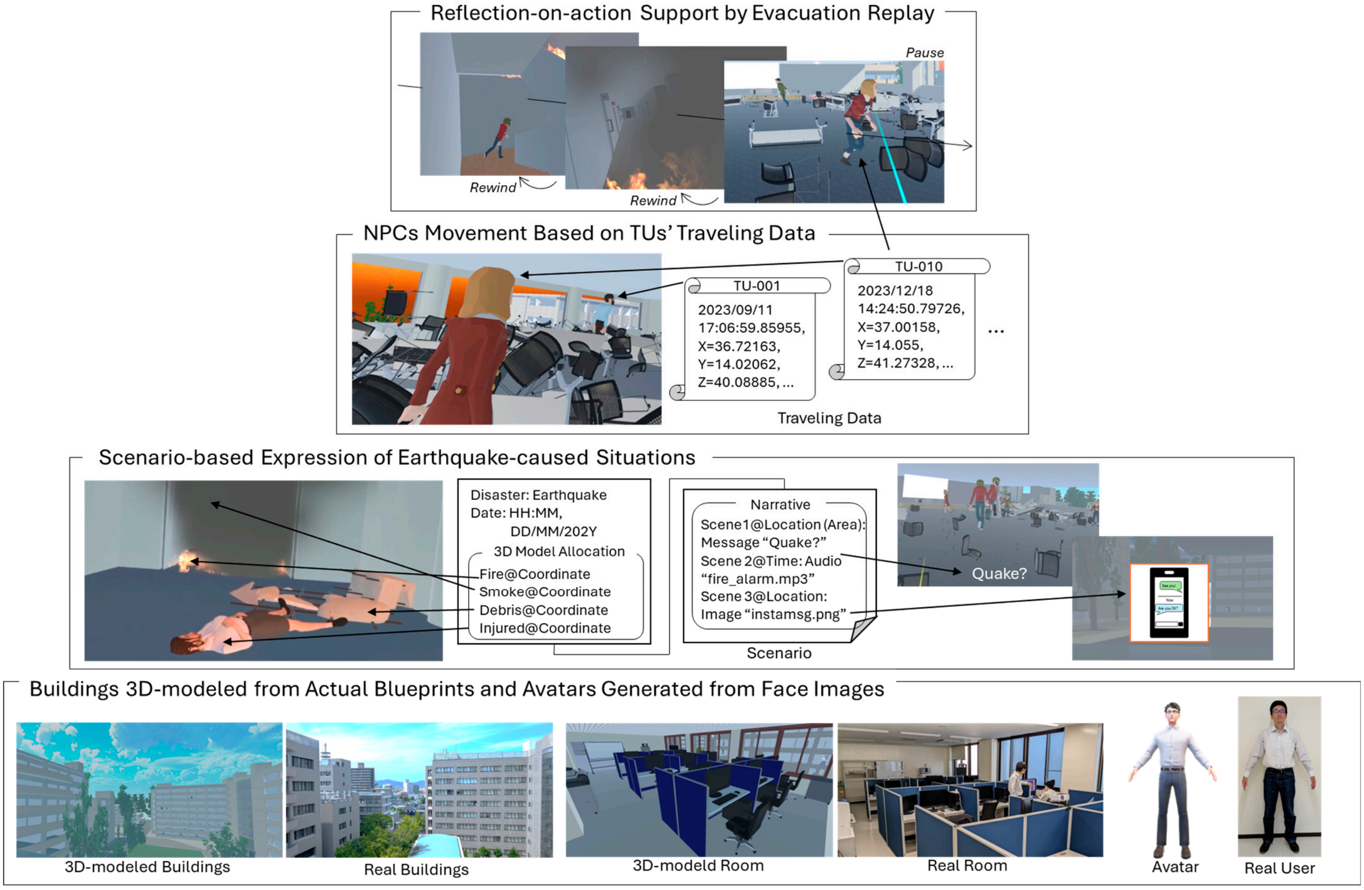


Figure 4. Metavearthquake characteristics.

4.1.1. Buildings 3D-Modeled from Actual Blueprints and Avatars Generated from Face Images

Tokudiverse provides a 3D virtual world faithful to the campus of Tokushima University. Buildings in the virtual world were 3D-modeled from actual blueprints with the 3D-CAD software "SketchUp". Some artificial and natural objects (e.g., furniture and trees) were 3D-modeled from scratch using the 3DCG modeling software "Blender", and others were adopted from Unity assets and free-licensed models. The 3D models composing the virtual world were imported into Unity and adjusted faithfully to actual sizes and locations.

Avatars resembling real users were created with the 3D avatar generation service "ReadyPlayerMe". This service generates a default avatar from a user's uploaded face image and enables the user to customize the avatar's appearance (e.g., hairstyle and clothing). A TU can see the virtual world from their avatar's view (i.e., first-person view) and move the avatar using the VR controllers or a keyboard (WASD-key operations). The avatar's view direction can follow the TU's head angle sensed by the VR headset, and the avatar's entire body can move naturally based on the TU's head and hands tracked with the Unity asset "Final IK". In other words, gesture communication via avatar is available.

4.1.2. Scenario-Based Expression of Earthquake-Caused Situations

Metavearthquake adopts a scenario-based expression of earthquake-caused situations. Each scenario is created based on a different supposition, such as "daytime earthquake, partial building collapse, and many injured" and "nighttime earthquake, earthquake-caused fire, and many panicked". A Tokudiverse administrator activates the VR application while selecting one scenario. When the ET phase ends, a new scenario is randomly selected and assigned to all TUs' VR applications. If a scenario such as the previous scenario is selected, the next stage is regarded as not the CE stage but the AE stage.

(1) Earthquake Occurrence

Each scenario designates one of the following modes to set when Metavearthquake will be activated, i.e., when an earthquake will occur in the virtual world.

- Arbitrary. This mode allows the administrator to generate an earthquake at an arbitrary timing by pressing a designated key on the host computer.
- Preset. This mode allows the administrator to set the date and time to generate an earthquake in advance.
- Real-world earthquake. This mode constantly monitors emergency earthquake information issued by the Japan Meteorological Agency (JMA) and generates an earthquake in the virtual world immediately after a real earthquake satisfying "JMA seismic intensity ≥ 4" (the default condition) occurs in Japan. For reference, 41 big earthquakes satisfying the default condition occurred in Japan in 2023. Based on this frequency, Metavearthquake would be activated approximately once every 9 days (the default condition could be changed to set more infrequency).

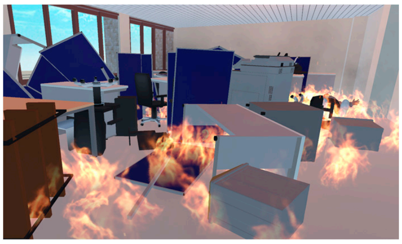
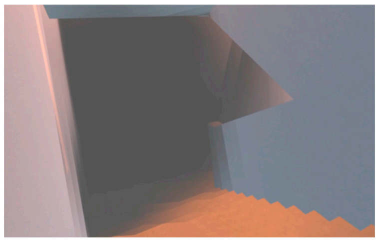
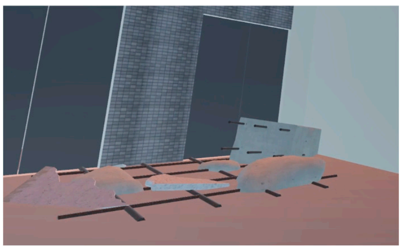
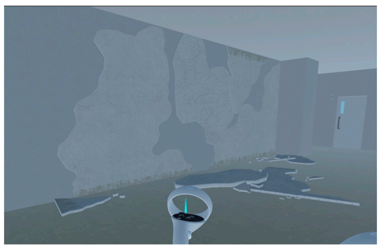
(2) Earthquake Shakes

To express earthquake shakes, Metavearthquake repeatedly moves the x-z plane of the virtual world at random variations. Three-Dimensional models of unfastened furniture (e.g., desks and chairs) sway and fall over according to physics calculations of the shakes. The more 3D models, the more calculation required, and the slower the rendering process. Thus, Metavearthquake actively adopts lower-polygon 3D models, primitive colliders, and occlusion culling (no rendering invisible models).

(3) Expression Methods of Earthquake-Caused Situations

Metavearthquake expresses earthquake-caused situations, as shown in Table 1. There are two expression methods.

Table 1. Earthquake-caused situations expressed by 3D model allocation.

Situation	Screenshot	Situation	Screenshot
Flame (and scattered furniture)		Smoke (covering stairs)	
Debris (concrete pieces and metal pipes)		Debris (collapsed wall)	
Injured (unconscious or severe)		Injured (stupor in wheelchair)	

- 3D Model Allocation. According to the selected scenario, 3D models expressing earthquake-caused situations are allocated in the virtual world immediately after the earthquake occurs. All models do not move from the initial positions; however, flame, smoke, and injured persons (NPCs) repeat small motions at the position. Each model is given a location (x, y, z coordinate), rotation (x, y, z quaternion), and scale (x, y, z proportion from standard size).
- Narrative Presentation. According to the selected scenario, digital contents (e.g., text, audio, and image) are superimposed onto the screen when an MP enters preset locations or when designated times have passed since the ET phase began. The preset locations and MPs' destinations (i.e., safe places) are defined as Unity box colliders set in the virtual world. In addition, narratives can be expressed in structures, as shown in Figure 5. Each narrative comprises one or more scenes corresponding to locations in the virtual world and designated times in the ET phase. Each scene comprises one or more cuts corresponding to digital content. For example, a structured narrative that an MP looks at a no-entry warning (text) in front of a non-earthquake-resistant building but enters the building and then hears someone's loud scolding (audio) will make the MP recognize the importance of accepting such a warning.

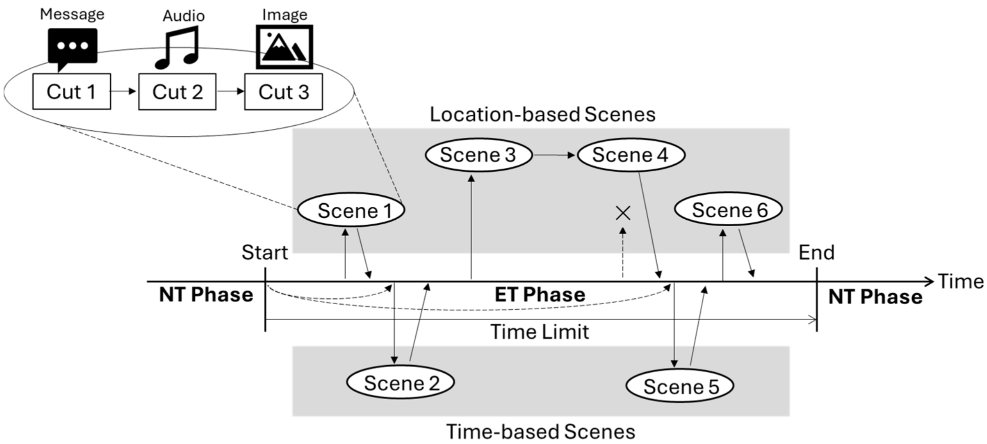


Figure 5. Structured scenario (narrative story) with scenes and cuts.

4.1.3. NPC Movement Based on TUs' Traveling Data

Metavearthquake introduces NPCs to express difficult human-caused situations [52]. In a real evacuation, people do not always take reasonable evacuation routes; some wander around in confusion, and others do not start evacuation because of cognitive biases. Thus, Metavearthquake does not determine (program) each NPC's reasonable evacuation route but moves NPCs based on TUs' traveling data during the ET phase in the same scenario. In other words, NPCs' movements are the reproduction of the TUs' previous movements and become diverse in that NPCs are mixed between those who evacuate (i.e., MPs) and those who do not (i.e., TUs excluding MPs). Figure 6 illustrates NPCs' movements based on TUs' traveling data. NPCs who are not evacuating represent people who are unaware of or optimistic about the earthquake-caused situations. If these NPCs are the majority, conformity bias may make TUs underestimate the situations and lose motivation to evacuate. NPCs who are evacuating represent people who are concerned about the earthquake-caused situations. If these NPCs are the majority, conformity bias may motivate TUs to evacuate but cause panic.

For each scenario, TUs' locations and rotations with time stamps are recorded as the traveling data. More specifically, each TU's VR application stores his/her traveling data in a queue at each frame and then transfers the stored data with his/her logon ID to the host computer, and the host computer records the received data into an external file for each scenario. The more the same scenario is used in the ET phase (AE stage), the more NPCs appear in that scenario.

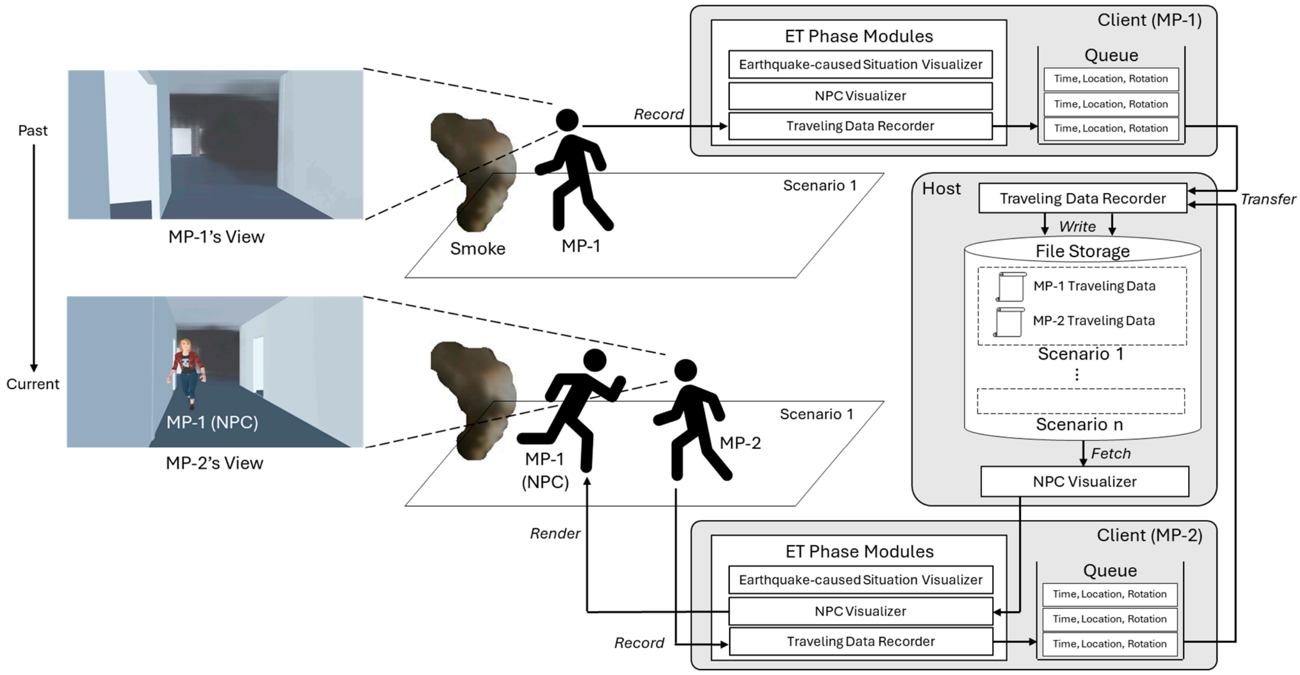


Figure 6. NPC movement based on TUs' traveling data.

4.1.4. Reflection-on-Action Support by Evacuation Replay

Reflection-on-action (i.e., RT phase) is not necessarily easy, even immediately after the ET phase, because MPs may experience difficulty recalling what decision they made in the ET phase. To support reflection-on-action, Metavearthquake replays an MP's evacuation, i.e., earthquake-caused situations and movements of the MP (avatar) and others (NPCs), in the corresponding scenario [53]. The MP can see his/her evacuation from either a first- or third-person perspective while pausing and rewinding the replay. This replay helps the MP to recall his/her decision making and complete the RT phase. For example, if it is replayed that the MP was wandering around an injured person, the MP may recall his/her indecision about whether to rescue the injured person and then identify that the failed evacuation was due to slow decision making.

4.2. User Interface

Tokudiverse requires users to register their names, logon IDs, passwords, and avatars (URLs to a created.obj file) to the web server application. Registering slideshows (PDF files) is allowed for faculty member TUs.

4.2.1. Scenario Creation Tool

Two scenario creation tools are prepared to set earthquake-caused situations. Currently, the tools work independently from Metavearthquake and are available only for Tokudiverse administrators. The created scenario is exported into an XML file and stored in the administrators' VR applications. Figure 7 shows screenshots of the scenario creation tools (Video S1).

- 3D Model Allocator. This tool enables a scenario creator (administrator) to enter the virtual world and allocate 3D models intuitively from the first-person view using a VR headset and controllers. More concretely, the scenario creator designates a location with a laser-pointer metaphor and allocates a selected 3D model at the location while adjusting its size and rotation (Figure 7a) [54].
- Narrative Editor. This tool enables the scenario creator to edit a narrative storyline and digital content through text and pulldown components (Figure 7b). The scenario

creator can control the narrative storyline by setting conditions. An example of a condition is that Scene-4 is unvisitable if Scene-3 has not been visited.

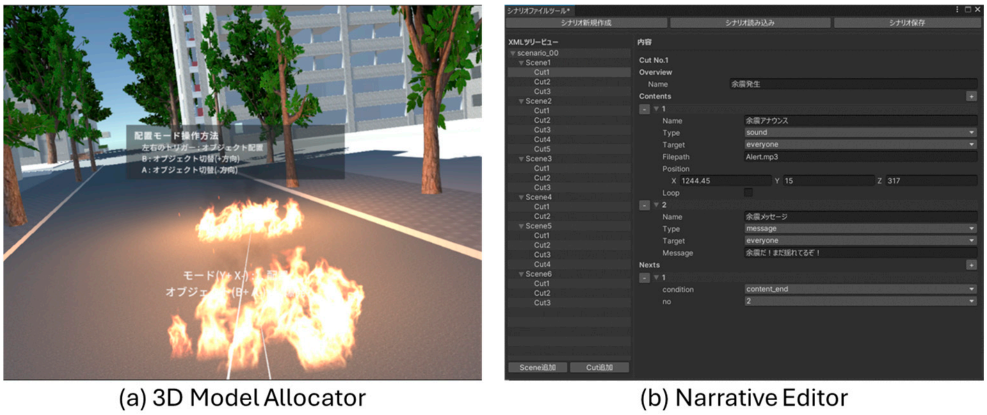


Figure 7. User interfaces of scenario creation tools: (**a**) Flames are allocated at the spot indicated by a pointer; (**b**) Scenes and cuts are defined and connected through text and pulldown components.

4.2.2. VR Application

Figure 8 shows screenshots of the VR application (Video S1). A TU sends his/her logon ID and password to the web server application via the VR application. If successfully authenticated, the TU (his/her avatar) is spawned into an initial location in the virtual world.

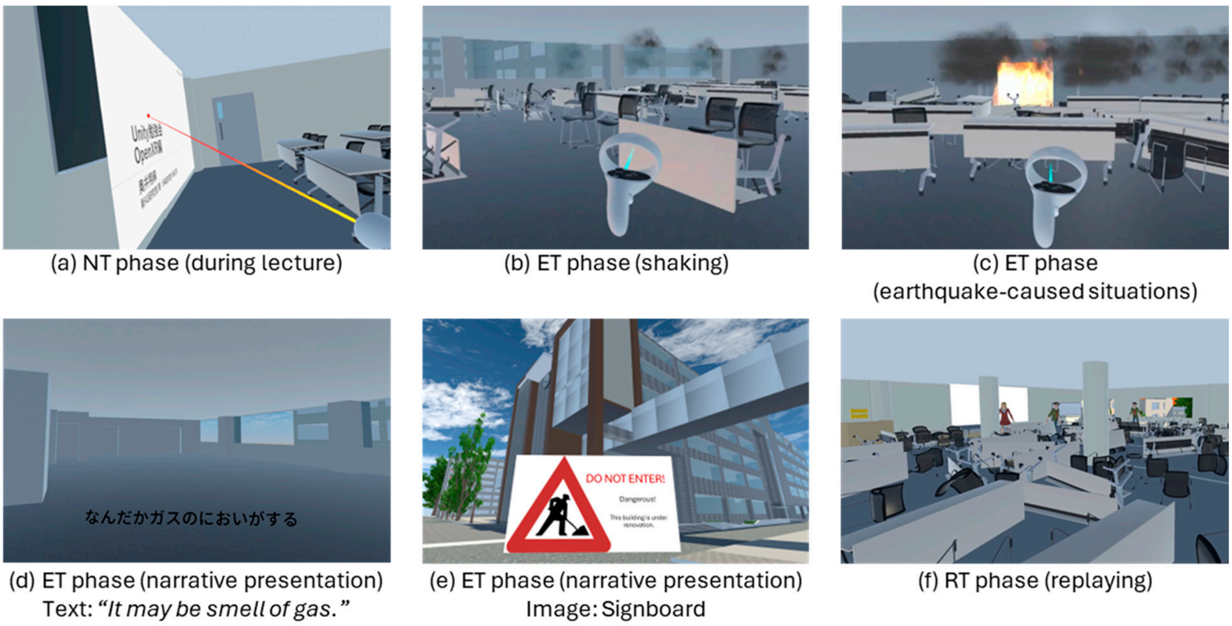


Figure 8. User interfaces of the VR application: (**a**) A faculty member TU is delivering a slideshow-based lecture; (**b**) An MP is enduring shakes that upset desks and chairs; (**c**) The MP is searching for an exit under earthquake-caused situations; (**d**) The MP recognizes gas leak (from the presented message); (**e**) The MP recognizes the dangerous area (from the presented signboard); (**f**) The MP is reflecting on evacuation behaviors (from the replay).

(1) NT Phase

TUs can communicate via voice chat and gestures. Faculty member TUs can present their slideshows on a lecture-room screen while flipping the slide and using a laser-pointer function (Figure 8a).

(2) ET Phase

Metavearthquake is activated according to the selected scenario and suddenly changes the NT phase to the ET phase along the following process:

- An earthquake early warning goes off for 5 s.
- The virtual world is shaken for 10 s, and unfastened furniture (3D models) scatters on the floor because of the shakes (Figure 8b).
- 3D models expressing earthquake-caused situations appear in the virtual world (Figure 8c).

Note that no messages are displayed to promote or instruct evacuation. MPs (avatars) can walk and sprint but cannot jump. MPs encounter earthquake-caused situations and make decisions. In a scene (i.e., when an MP visits a preset location or a preset time arrives), one or more digital contents, such as a message (Figure 8d) and an image (Figure 8e), are superimposed on the screen. Even if colliding with debris, flame, and smoke, MPs are not injured (e.g., bleed, burn, or cough); MPs never die. In addition, even if colliding with injured persons (NPCs), MPs cannot interact with them. Currently, Metavearthquake focuses on the successful evacuation of MPs; therefore, MPs cannot perform rescue activities. When a designated time has elapsed since the earthquake occurrence, the ET phase ends and transitions to the NT phase; Metavearthquake is inactivated, and all earthquake-caused situations disappear.

(3) RT Phase

At an arbitrary timing in the NT phase, TUs can shift to the RT phase to perform reflection-on-action regardless of whether they have evacuated successfully in the ET phase (Figure 8f) (only MPs transition to the RT phase). The menu for the RT phase is presented at the initial location. The reflection-on-action support function allows MPs to thoroughly observe their evacuation (behaviors in the ET phase) and recall their decision making by seeing, rewinding, and pausing the replay.

5. Experiment

Several topics related to Metavearthquake should be investigated, but the most important is whether Metavearthquake is feasible for evacuation training use. This experiment focused on the ET phase and roughly investigated the validity of evacuation training that began with a sudden earthquake in the virtual world. The primary aim of this experiment was to estimate the feasibility of using Metavearthquake as a metaverse-based evacuation training system by monitoring evacuation behaviors, emotions, and training effects among three groups that differed in terms of earthquake notification before accessing Tokudiverse. The current research questions (RQs), which may provide insights into a future metaverse-based evacuation training system, were set as follows:

- RQ1. How do subjects (TUs) behave in the ET phase?
- RQ2. What emotions do subjects have in the ET phase?
- RQ3. What training effects are introduced in the ET phase?
- RQ4. Do subjects accept Metavearthquake?

5.1. Settings

Metavearthquake should be investigated under practical conditions where many TUs are simultaneously in the virtual world. However, such conditions were not feasible. Thus, the experiment adopted a quasi-experimental design following the condition that one subject and some NPCs are in the virtual world.

5.1.1. Subjects

Tokushima University students were notified that volunteers were required to test a metaverse prototype, "Tokudiverse", and 30 male students (aged 19–24) volunteered to participate in the test. Based on their responses to a prequestionnaire asking about knowledge and experience of the metaverse and VR (Appendix B), the volunteers were evenly divided into three groups that differed in notification of earthquake occurrence before accessing Tokudiverse. In each group, three or four participants had VR experiences while seven to nine participants had knowledge but no experience of the metaverse.

- Group A (N = 10). Subjects were notified that an earthquake would occur in Tokudiverse with the definitive words, "You encounter an earthquake during your test play". It was predicted that they would be mentally ready for the earthquake occurrence and aware of the necessity of evacuation.
- Group B (N = 10). Subjects were notified that an earthquake would occur in Tokudiverse with the vague words, "You may encounter an earthquake during your test play if unlucky". It was predicted that they may be mentally ready for the earthquake occurrence and estimate the necessity of evacuation. The subjects can be regarded as the majority of TUs, who have already encountered or heard about a sudden earthquake in Tokudiverse.
- Group C (N = 10). Subjects were not notified that an earthquake would occur in Tokudiverse. In other words, they suddenly encountered the earthquake without being mentally ready for the earthquake's occurrence.

5.1.2. Scenario and NPCs

The scenario used in the experiment assumed that students encountered a mega earthquake in a six-story lecture building, and a fire occurred inside the building. Thus, the subjects were expected to exit the building from the first-floor entrance. The time limit was 20 min. Injured people were not allocated to the virtual world, and the narrative presentation was not adopted. These conditions were adopted so that the subjects would concentrate on their evacuation (i.e., wayfinding) without narrative interpretation, especially because the system did not enable them to perform rescue activities. Flames, smoke, and debris were distributed on floors as earthquake-caused situations. The subjects were unable to move beyond flame and debris and thus were forced to make a detour if the route was blocked. In addition, all doors leading to the exterior stairs were locked. As a result of the allocations and the locked doors, only one evacuation route was available.

A total of 15 NPCs were allocated. Eight of nine NPCs who started evacuation successfully exited the building despite going back and forth on the way; one abandoned the evacuation on the way and could not exit the building within the time limit. Six NPCs were allocated to express difficult human-caused situations, i.e., cognitive bias not to motivate evacuation; four and two NPCs stayed around flames and at the places where they encountered the earthquake, respectively. Figure 9 illustrates the scenario focusing on earthquake-caused situations and NPCs.

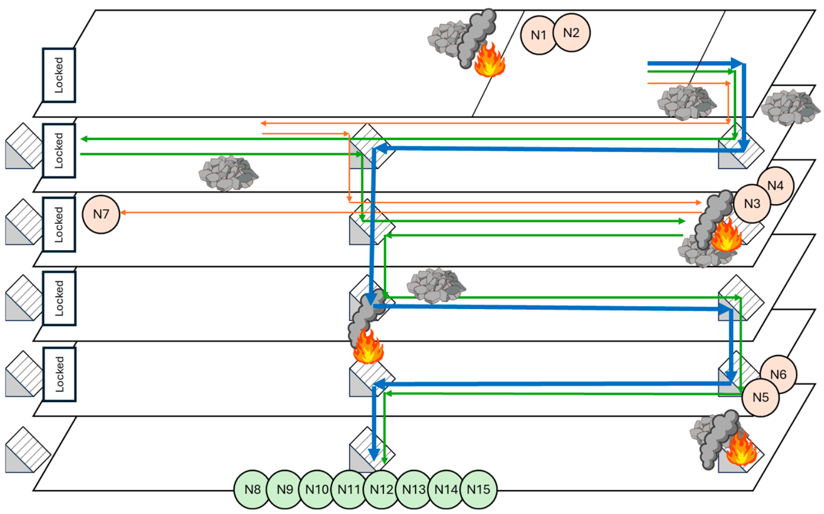


Figure 9. Scenario focusing on earthquake-caused situations and NPCs in lecture building. N1–N6 remained in their locations. N7 attempted to evacuate but abandoned the evacuation on the way. N8–N15 successfully evacuated. The blue line indicates the only available evacuation route.

5.1.3. Procedure

Figure 10 shows the experimental procedure. After filling out the prequestionnaire, each subject joined the test play (experiment) at a different time. Each subject verbally received a notification of the possible earthquake occurrence (for Groups A and B) and explanations of how to operate the avatar while wearing Meta Quest 2. In the test play, although standing was recommended, sitting was permitted if the subject was prone to VR sickness. After understanding the explanations, the subject (avatar) was spawned near the entrance outside the lecture building and required to reach a lecture room on the sixth floor. Note that all subjects had been attending lectures in the real-world lecture building daily. The experimental procedure after reaching the lecture room was as follows:

- The subject was requested to play darts for a while.
- An experimenter (Tokudiverse administrator) activated Metavearthquake when the subject was concentrating on the play; the subject transitioned from the NT phase to the ET phase. (See Section 3.2.1 for details on the ET phase.)
- A fire alarm started ringing inside the building and kept ringing during the ET phase. This earthquake-caused situation indicated that the subject had to exit the building to escape from the fire.
- The subject decided whether to evacuate. Note that the experimenter never instructed evacuation.
- The ET phase lasted for 20 min. If they exited the building within 20 min, the subject was recognized as a successful evacuee. During the ET phase, the subject's traveling data were recorded. The time and distance from the moment the shakes stopped to the moment the subject exited the building were measured as the evacuation time and distance, respectively. In addition, the subject was videotaped to record utterance, and the screen was captured.
- After the ET phase, the subject filled out a postquestionnaire.

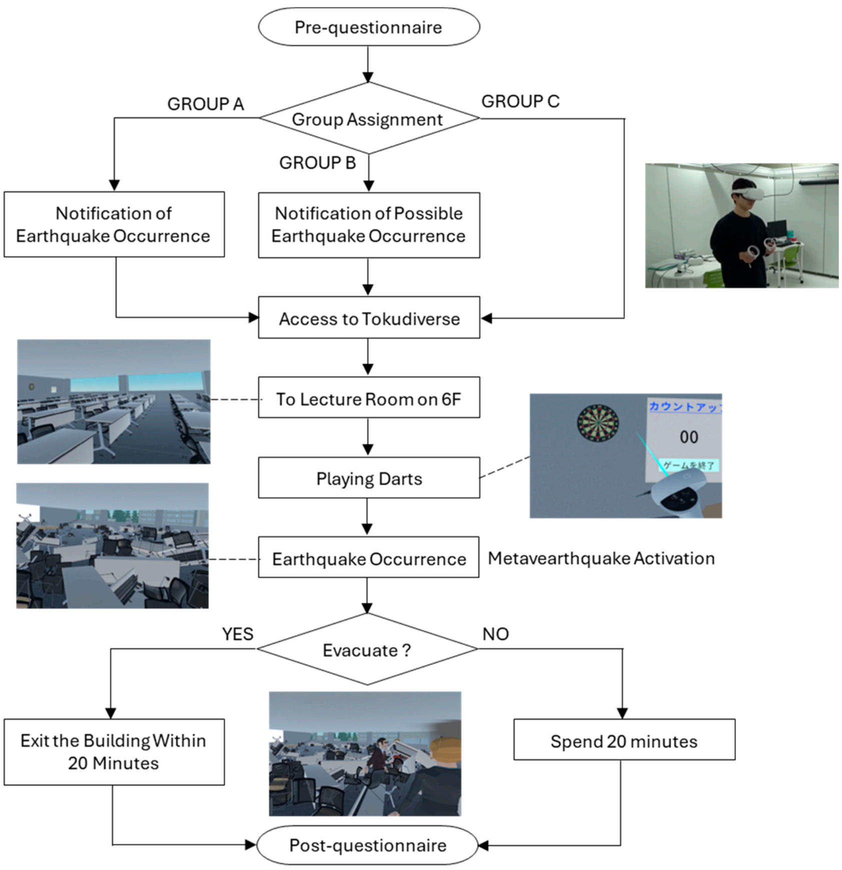


Figure 10. Experimental procedure.

5.2. Results

The experiment did not observe self-efficacy, which is frequently evaluated in VR-based evacuation training systems, because Metavearthquake considers self-efficacy an emotion or a training effect obtained through repetitive circulation of the evacuation training model.

5.2.1. Evacuation Behaviors

The traveling data showed that 28 out of 30 subjects started evacuation. Through the postquestionnaire, the subjects were asked to write down why they started evacuation or did not evacuate; multiple reasons were allowed. The dominant reason in the three groups was "I had to evacuate due to the earthquake and fire" (six, seven, and five subjects in Groups A, B, and C, respectively). The next dominant reasons were "I was influenced by others (NPCs)" (one, three, and one in A, B, and C, respectively), "It was evacuation training" (two and one in A and C, respectively), and "I thought evacuation is a part of the game" (one and one in B and C, respectively). Two subjects (B7 and B8) in Group B did not start evacuation for the following reasons: "I guessed I was being requested to keep playing darts regardless of the earthquake" (B7) and "I did not know what to do and thought that staying in the room was safest" (B8). One subject (C6) in Group C started evacuation but abandoned evacuation midway because of VR sickness, and another subject (C7) was stuck between 3D models and unable to move after the shakes stopped and thus delayed starting evacuation.

Twenty-seven subjects, except for B7, B8, and C6, successfully evacuated by exiting the building within the time limit. Table 2 shows evacuation behavior data (B7, B8, C6, and C7 excluded). Under the assumption of normality and homoscedasticity, the obtained data were statistically analyzed using a one-way analysis of variance (ANOVA). Note that the assumption was not completely satisfied for the Shapiro–Wilk test that analyzed Group C's evacuation time and Group B's time spent leaving the lecture room but was adopted because of the test's uncertainty due to the small sample size. The mean values of the evacuation time ranged from 148.6 to 222.0 s, and there was no significant difference between the three groups. The mean values of the evacuation distance were 415.6–518.8 m, and there was no significant difference between the three groups. The mean values of the time spent leaving the lecture room were 42.6, 37.5, and 80.6 s for Groups A, B, and C, respectively, demonstrating a significant difference (p = 0.029) at the 5% level. Tukey's multiple comparison test revealed a significant difference in the mean values (p = 0.041) at the 5% level between Groups B and C. The traveling data and the captured screens showed that four subjects in Group C walked around the lecture room for a while and then found the only exit. The postquestionnaire for Group C revealed that two subjects experienced difficulty comprehending the situation and waited for someone's instructions for a while, and one subject took time to recall that the lecture room has two exit points.

Table 2. Mean values regarding evacuation behaviors.

	Group A (N = 10)	Group B (N = 8)	Group C (N = 8)	ANOVA
E-Time	176.8 s (64.8 s)	148.6 s (40.7 s)	222.0 s (109.9 s)	F (2, 23) = 1.88, p = 0.175
E-Dist	483.9 m (161.7 m)	415.6 m (125.1 m)	518.8 m (107.4 m)	F (2, 23) = 1.19, p = 0.320
TSLLR	42.6 s (11.5 s)	37.5 s (11.3 s)	80.6 s (57.8 s)	F (2, 23) = 4.10, p = 0.029

E-Time, E-Dist, and TSLLR indicate evacuation time, evacuation distance, and time spent leaving the lecture room, respectively. Value in the parentheses is the standard deviation (SD).

The traveling data and the captured screens showed that almost all subjects detoured from flames as soon as they spotted the exit after leaving the lecture room, but many subjects tended to move through smoke (six, seven, and seven subjects in Groups A, B, and C, respectively). In addition, in the overall evacuation process, many subjects tended to chase the NPCs who were evacuating (eight, five, and six in A, B, and C, respectively).

The video data showed that when the shakes started, many subjects regardless, of the groups, uttered words such as "What's going on?", "It's an earthquake!", and "Scared!" During the evacuation, a few subjects uttered words such as "Where will you go?" and "Do you know the exit?" to the NPCs.

5.2.2. Emotions

The postquestionnaire asked all subjects about their emotions in the ET phase. Table 3 shows the medians for emotions collected with five-point Likert scale questions. Owing to the ordinal scale, the obtained data were statistically analyzed using the Kruskal–Wallis test by assuming non-normality and heteroscedasticity. The medians for fear were 3.5, 3, and 2 for Groups A, B, and C, respectively, and the mean ranks showed a significant difference (p = 0.022) at the 5% level. The Steel–Dwass test (multiple comparison) revealed a significant difference in the mean ranks (p = 0.016) at the 5% level between Groups A and C. The mean ranks for anxiety, frustration, confusion, and enjoyment showed no significant differences between the three groups.

Table 3. Medians regarding emotions.

	Group A (*N* = 10)	**Group B (*N* = 10)**	**Group C (*N* = 10)**	**Kruskal–Wallis Test**
Fear	3.5 (21.20)	3 (14.45)	2 (10.85)	χ^2 (2) = 7.60, p = 0.022
Anxiety	4 (17.30)	3.5 (15.50)	3.5 (13.70)	χ^2 (2) = 0.92, p = 0.630
Frustration	4 (18.30)	4 (14.25)	4 (13.95)	χ^2 (2) = 1.76, p = 0.412
Confusion	4 (15.05)	4 (16.50)	4 (14.95)	χ^2 (2) = 0.24, p = 0.886
Enjoyment	3 (14.90)	4 (16.10)	4 (15.50)	χ^2 (2) = 0.10, p = 0.950

The value in parentheses denotes the mean rank. The question template was "Do you agree that you felt <emotion> after the earthquake has happened?" The options were "5. Strongly agree", "4. Agree", "3. Neutral", "2. Disagree", and "1. Strongly disagree".

5.2.3. Training Effects

Training effects were measured primarily based on the subjects' self-evaluation scores of evacuations and the number of awarenesses obtained in the ET phase. Table 4 lists the mean values and medians for training effects obtained through postquestionnaire. Note that C6 was asked to answer the questions about training effects while focusing on the evacuation process up to evacuation abandonment, and B7 and B8 were asked to write down their awarenesses but did not evacuate (did not exit the building).

Table 4. Mean values and medians regarding training effects.

	Group A (*N* = 10)	**Group B (*N* = 8)**	**Group C (*N* = 10)**	**ANOVA**
SS	70.5 (13.42)	57.5 (26.72)	43.0 (15.67)	F (2, 25) = 5.35, p = 0.011
	Group A (*N* = 10)	**Group B (*N* = 10)**	**Group C (*N* = 10)**	**Kruskal–Wallis Test**
NoA	2 (11.00)	2.5 (18.50)	2.5 (17.00)	χ^2 (2) = 4.73, p = 0.093

SS indicates self-evaluation score (mean) and NoA denotes the number of awarenesses (median). Values in the parentheses represent SD for SS and mean rank for NoA. Subjects were asked to write down self-evaluation and awarenesses through "Please self-evaluate your evacuation and score it between 0 and 100", "Please write down the reasons for your self-evaluation score", and "Please itemize your awarenesses obtained through this metaverse experience".

For the self-evaluation of the evacuation, the obtained data were statistically analyzed with ANOVA based on their confirmed normality and homoscedasticity. The mean scores for the self-evaluation of the evacuation (0–100) were 70.5, 57.5, and 43.0 for Groups A, B, and C, respectively, and showed a significant difference (p = 0.011) at the 5% level. Tukey's multiple comparison test revealed a significant difference in the mean scores (p = 0.008) at the 1% level between Groups A and C. The self-evaluation scores of Groups A, B, and C were in ranges of 50–90, 15–100, and 20–70, respectively (the scores of C6 and C7 were both 50). In the three groups, the dominant reasons for low self-evaluation were "I did not evacuate speedily", "I did not evacuate calmly", and "I did not make quick or proper decisions". In Group C, the following reasons were found: "I was prevented from thinking of better evacuation routes due to the sudden earthquake" and "I was confused and had no idea about what to do even after the shakes stopped". A dominant reason for high self-evaluation was "I evacuated speedily".

For awarenesses in the ET phase, the obtained data were statistically analyzed using the Kruskal–Wallis test based on their confirmed non-normality and heteroscedasticity. The medians for the numbers of awarenesses were 2, 2.5, and 2.5 for Groups A, B, and C, respectively, and there was no significant difference between the three groups. In the three groups, the following common awarenesses were found: "I should behave calmly" (four, three, and five subjects in Groups A, B, and C, respectively), "I should know some evacuation routes" (four, two, and four in A, B, and C, respectively), and "I should grasp surroundings" (three, two, and two in A, B, and C, respectively). B7 and B8 wrote down their awarenesses as follows: "I should behave adaptively to any circumstances" and "I should be ready for disasters by myself to quit simply following others".

All subjects were asked to give their honest opinions about evacuation training that begins with a sudden earthquake in a virtual world, i.e., Metavearthquake. Fourteen subjects (six, three, and five subjects in Groups A, B, and C, respectively) provided positive opinions about Metavearthquake while emphasizing the fact that an earthquake suddenly occurs in the real world. Major positive opinions were "It is more realistic than traditional evacuation training", "Fear and confusion in evacuation can be simulated", and "It is effective for those who are not ready for an earthquake". Conversely, three subjects in Group A and four subjects in Group C provided negative opinions because they found fewer differences from evacuation training with notice beforehand, i.e., conventional VR-based evacuation training, in terms of predicting earthquake occurrence in the virtual world. Note that these seven subjects were positive about some effects of Metavearthquake, such as the provocation to think about evacuation routes.

5.3. Discussion

5.3.1. Evacuation Behaviors

Many subjects started evacuation even though the experimenter never instructed evacuation. These subjects may have been immersed in the virtual world and perceived threats to their lives and the necessity of evacuation even in the virtual world. However, two subjects (B7 and B8) did not start evacuation, and two other subjects (B6 and C6) started evacuation while regarding evacuation as a game. B8's decision seemed to result from thinking about whether to evacuate. However, B6, B7, and C6 may have been influenced by gaming elements and felt that the virtual world was different or disconnected from the real world. These results indicate that Metavearthquake (Tokudiverse) should be faithful to the real university environment without extra gaming elements to provide more realistic simulated evacuation experiences.

The mean values regarding evacuation behaviors showed that Group B completed evacuation most efficiently, whereas Group C performed it most inefficiently. In particular, Group C spent the longest time leaving the lecture room, with a significant difference from Group B. These results indicate that the sudden earthquake surprised the subjects in Group C, and some of them were upset and panicked. The subjects in Groups A and B tended to chase the NPCs who started the evacuation. In contrast, four subjects in Group C did not chase the NPCs, maybe because they could not afford to be aware of the NPCs. The observed evacuation behaviors indicate that the sudden earthquake influenced evacuation behaviors at a certain time after the shakes stopped and made simulated evacuation experiences more realistic and difficult. The subjects in Group B, who had been notified about a possible earthquake occurrence, may have been mentally ready for the sudden earthquake and could evacuate calmly. The subjects in Group A, who had been notified about an earthquake occurrence, may also have been ready to evacuate from the beginning but did not necessarily evacuate efficiently. The evacuation behaviors depended on not only their evacuation routes and encountered earthquake-caused situations but also on their personality and intentions. For example, four subjects in Group A tended to detour by seeing flames reflected on the wall. These subjects may have been careful about danger or attempted to become exemplary evacuees. In contrast, one subject in Group C tended to approach the flames. This subject may have been careless or reckless. Although not only flames but also smoke can be life-threatening, many subjects moved through smoke. Such subjects may have underestimated the danger of smoke.

- RQ1. How do subjects (TUs) behave in the ET phase?

Almost all subjects began evacuation regardless of whether they had been notified about the earthquake occurrence, and many subjects successfully evacuated. The sudden earthquake surprised and panicked the subjects but did not undermine the feasibility of the evacuation training. Earthquake- and human-caused situations (e.g., flame and NPCs) influenced the subjects' evacuation behaviors. The comprehensive answer to RQ1 is that Metavearthquake satisfies a prerequisite for evacuation training that induces evacuating in the virtual world.

5.3.2. Emotions

Regarding fear and anxiety, Group A exhibited the highest values for medians and mean ranks, whereas the mean ranks of Group C were the lowest. In the three groups, the medians for collected emotions were not extremely high or low (2–4). Differences in the medians for frustration, confusion, and enjoyment among the three groups were zero or a small value (within 1.0). A significant difference was found for fear between Groups A and C. From the observed evacuation behaviors, the medians (and mean ranks) of Group C for the investigated emotions were predicted to be the highest, except for enjoyment, due to sudden earthquake. However, contrary to the prediction, the subjects in Group A tended to be more scared, anxious, and frustrated than those in the other groups. Emotions vary significantly among individuals, and it is difficult to claim definitive differences between the groups from the observed emotions. However, it is possible to interpret that the subjects in Group C had no room for emotions such as fear and concentrated on evacuating. Conversely, the subjects in Group A, who were aware of the evacuation training, may have analyzed their emotions calmly, objectively, and negatively; they may have performed reflection-in-action in the ET phase. This interpretation leads to the hypothesis that the sudden earthquake makes simulated evacuation experiences more realistic but may not provoke subjects to recall their evacuation and consider how to evacuate. Medians for confusion can be interpreted positively in terms of simulating more difficult decision making. Similarly, medians for enjoyment can be interpreted positively to promote continuous access to Tokudiverse.

- RQ2. What emotions do subjects have in the ET phase?

Although only five emotions were investigated, the subjects exhibited moderate levels of fear, anxiety, frustration, confusion, and enjoyment emotions. However, the observed emotions were not traumatic or sufficient to discourage access to Tokudiverse. For example, confusion and enjoyment are required to heighten training effects and promote repetitive participation in evacuation training. The sudden earthquake can make simulated evacuation experiences more realistic but lower training effects by difficult reflection-in-action. Thus, reflection-on-action, i.e., the RT phase, should be sufficiently supported. The comprehensive answer to RQ2 is that Metavearthquake causes emotions that can lead to high training effects, and that the RT phase is indispensable.

5.3.3. Training Effects

The mean scores for self-evaluation indicated a significant difference at the 1% level between Groups A and C. The subjects in Group A tended to behave carefully for a steady evacuation, and they completed the evacuation. The carefulness and successful evacuation may have led to higher self-evaluation scores. In contrast, nine subjects in Group C (except for C6) completed the evacuation; however, their self-evaluation scores were lower. They may have attributed their low self-evaluation scores to the sudden earthquake that caused surprise and panic. However, given the low self-evaluation scores, a positive interpretation is that the subjects were unsatisfied with their evacuation and wanted to improve it. If the RT phase was provided in the experiment, they would have reflected on their evacuation and obtained concepts for successful evacuation. The mean score of Group B was intermediate; however, the SD of Group B was higher than that of the other groups. This may have depended on whether the subjects predicted the earthquake occurrence from the notification. The sudden earthquake may have emphasized their insufficient readiness for the earthquake and induced difficult decision making. The not-too-high self-evaluation scores of Groups B and C can be positively interpreted as training effects in that they could expect the transition to the RT or ET phase.

Both the number and content of obtained awarenesses were similar between the three groups, and all subjects (including B7 and B8) wrote down awarenesses, which were useful to identify factors of successful or failed evacuation. These results indicate that Metavearthquake provides training effects regardless of whether TUs evacuate. If the subjects had transitioned to the RT phase, their awarenesses would have been transformed into concepts. In other words, following the evacuation training model could have led to higher training effects.

- RQ3. What training effects are introduced in the ET phase?

Almost all subjects started evacuation, and their self-evaluation scores were not too high. In other words, they evacuated regardless of the groups and recognized the necessity of further evacuation training. In addition, they obtained awarenesses useful for future successful evacuation from their simulated evacuation experiences. The comprehensive answer to RQ3 is that Metavearthquake provides a fundamental training effect in the ET phase.

5.3.4. Summary

The answers to the above RQs maintain that Metaversequake has no remarkable disadvantages in terms of evacuation behaviors, emotions, and training effects in the ET phase. The sudden earthquake made simulated evacuation experiences and decision making more realistic and difficult but did not prevent the subjects from evacuating in the virtual world. For example, difficulties such as extreme fear have not been reported. In addition, there were no strongly negative opinions on the sudden earthquake. Thus, the sudden earthquake should be continuously adopted while encouraging MPs to transition to the RT phase.

The experiment involved three groups that differed in terms of prior earthquake occurrence notification. The TUs unfamiliar with Metavearthquake (i.e., a sudden earthquake in Tokudiverse) belong to Group C in the experiment. Once such TUs encounter an earthquake, they become familiar with Metavearthquake and recognize that an earthquake occurs occasionally in Tokudiverse. Thus, the majority of the TUs belong to Group B in the experiment. Focusing on the experimental results of Group B, two subjects did not start evacuation. However, the other subjects evacuated most efficiently and obtained meaningful simulated evacuation experiences. In the real world, earthquake occurrences are known, and everybody recognizes the possibility. Thus, the sudden earthquake is indispensable as the primary characteristic of Metavearthquake to simulate realistic evacuation experiences.

- RQ4. Do subjects accept Metavearthquake?

Based on the above discussion, the comprehensive answer to RQ4 is that the subjects accepted Metavearthquake as a metaverse-based evacuation training system. This makes TUs feel they must evacuate even in the virtual world.

5.4. Limitations

This experiment focused on the ET phase and roughly investigated Metavearthquake. The results and discussions have limitations. A significant limitation is that the statistical analysis results are not reliable due to the small number of subjects. In addition, the experiment was not conducted in practical settings such as multiuser environments, and the subjects could not communicate with other subjects via voice chat and gesture. Expressing difficult human-caused situations by NPCs only may be insufficient. Another significant limitation is that the experiment did not follow the evacuation training model. In other words, the experiment was not conducted in the long term. In particular, to investigate training effects, practical settings are required where subjects frequently access Tokudiverse in the long term and have been in the ET and RT phases (i.e., CE, RO, AC, and AE stages) several times by following the evacuation training model.

At this point, the experimental results simply show that Metavearthquake can be used for evacuation training. Further comparison experiments with conventional evacuation training systems should be performed to verify the true value of Metavearthquake in the long term. For example, future studies must clarify the superior cost-effectiveness of Metavearthquake compared to conventional systems to enable its widespread utilization. Furthermore, the application of the experimental results to real-world evacuation must be investigated. Previous studies have focused on whether evacuation behaviors (e.g., wayfinding [55], exit choice [56], and crowd chase [57]) observed in VR disaster simulators were identical to those in the real world and argued that the observed behaviors were similar to real-world evacuation behaviors and can be employed for successful evacuation (e.g., evacuation route and sign designs). However, whether VR-based evacuation training systems provide better training effects than real-world evacuation training remains understudied. For example, knowledge transfer from VR-based evacuation training to real evacuation should be investigated. Such an investigation is extremely difficult to perform but should be conducted in Metavearthquake.

6. Conclusions

This study presented a metaverse-based evacuation training system focusing on earthquake evacuation, "Metavearthquake", describing its design, implementation, and experimental results. The prototype system functions as a part of an original university metaverse service, "Tokudiverse", and aims at providing more realistic, effective simulated evacuation training than conventional VR-based evacuation training systems. The main characteristic of Metavearthquake is that evacuation training begins unexpectedly due to a sudden earthquake in the metaverse (virtual world) that simulates a real university campus. In other words, providing users (TUs) with earthquake evacuation training that entails the decision making process under mentally challenging circumstances is the biggest advantage of Metavearthquake. Other characteristics include scenario-based expression of difficult earthquake-caused situations and NPC-based expression of difficult human-caused situations. Metavearthquake is based on an evacuation training model that comprises three phases: NT, ET, and RT. An earthquake suddenly occurs in the NT phase, and participants transition to the ET phase. In the ET phase, participants are required to evacuate to a safe place while making decisions in difficult situations. In the RT phase, participants reflect on their evacuation (decision making) via evacuation replay. The VR application of Metavearthquake was implemented using Unity, OpenXR, and Photon to ensure multiplatform capabilities, VR device compatibility, and multiuser accessibility. The experiment was conducted in three groups that differed in terms of notification of earthquake occurrence before accessing Tokudiverse. The experimental results, including statistical analysis results, imply that a sudden earthquake is indispensable for realistic simulated evacuation experiences and that Metavearthquake is an effective metaverse-based evacuation training system in terms of evacuation behaviors, emotions, and training effects. Conventional VR-based evacuation training systems have not intensively explored creating situations where evacuation training begins unexpectedly due to a sudden disaster.

This is because those systems assume that the training effects will not be diminished even if participants know that evacuation training will begin. The experimental results indicate that a metaverse-based evacuation training system like Metavearthquake can be a new type of evacuation training system. The key finding is that the validity of metaverse-based evacuation training has been demonstrated and will be a catalyst for further development and practice.

Metavearthquake (and Tokudiverse) is still under development. For example, the virtual world has been modeled faithfully on a real campus but should be improved in terms of visual reality (e.g., shading). In addition, interactivity with objects and NPCs should be improved to make simulated evacuation experiences more realistic. Currently, Metavearthquake does not focus on rescue activities during evacuations that occasionally entail moral dilemmas and difficult decision making. This focus can be extended to an ethics matter concerning how death should be treated and expressed in Metavearthquake. If exploring reality, Metavearthquake should not give the right of resurrection to participants who behave recklessly (e.g., jumping from a height); participants would die if they behaved in such a manner in the real world. However, Metavearthquake is built on Tokudiverse; therefore, participants expect to be resurrected and to continuously enjoy their usual comfortable virtual world. A key issue in Metavearthquake is the balance between reality and virtuality or training and metaverse services.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/mti8120112/s1, Video S1: Tokudiverse and Metavearthquake. This video shows a process of evacuation training consisting of normal, emergency and reflection phases.

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Appendix A

The following original acronyms (abbreviations) were used in this article.

- ETM: Evacuation Training in the Metaverse
- NT: Normal Time
- ET: Emergency Time
- RT: Reflection Time
- TU: Tokudiverse User
- MP: Metavearthquake Participant
- CE: Concrete Experience
- RO: Reflective Observation
- AC: Abstract Conceptualization
- AE: Active Experimentation
- E-Time: Evacuation Time
- E-Dist: Evacuation Distance
- TSLLR: Time Spent Leaving Lecture Room
- SS: Self-evaluation Score

- NoA: Number of Awarenesses

Appendix B

Subjects were asked following questions in the prequestionnaire.

- Name
- Age
- Sex: "Male", "Female", or "I avoid answering".
- "Do you have VR experience?": "Yes" or "No"
- "Do you know what metaverse is?": "Yes" or "No"
- "What kind of VR (including metaverse) did you experience?"

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