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Evacuation Drill Using Augmented Reality and a Handheld Head-Mounted Display

Hiroyuki MITSUHARA[a*], Hiroki IRIE[b], & Masami SHISHIBORI[a]
[a]*Graduate School of Technology, Industrial and Social Sciences, Tokushima University, Japan*
[b]*Graduate School of Advanced Technology and Science, Tokushima University, Japan*
*mituhara@is.tokushima-u.ac.jp

Abstract: Evacuation drills are very common as disaster education. However, an evacuation drill is not necessarily very realistic. To heighten the reality, we proposed an ICT-based evacuation drill (ICTBED) and developed ICTBED systems. One of our ICTBED systems aimed to achieve a high degree of reality using augmented reality (AR) and an immersive head-mounted display (HMD) but was impractical as disaster education. To make the system practical, we focused on AR and a handheld HMD (HHMD) and, then, prototyped the HHMD system. This paper describes the HHMD system and focuses on how to visualize disaster situations using AR. We report on a preliminary experiment at an educational event for children.

Keywords: Augmented reality, evacuation drill, disaster education, head-mounted display

1. Introduction

Disasters can happen to anyone. In recent years, the number of natural disasters has been increasing. In addition, we must be mindful of non-natural disasters (e.g., terrorist attacks). Thus, disaster management (disaster risk reduction) is important for us to survive disasters. Disaster management is roughly divided into structural and non-structural measures. For example, for a tsunami (seismic tidal wave), a typical structural measure would be a coastal levee and a typical non-structural measure would be an evacuation drill. Even if the structural measures seem to be sufficient, whether we survive a disaster depends on our decisions (and actions) based on our knowledge, skill, and experience. This means that we must learn how to survive disasters. In other words, disaster education is a very important non-structural measure.

Evacuation drills are a very common form of disaster education. However, in many cases, evacuation drills differ from reality (i.e., real evacuations). Conventional evacuation drills tend to make participants simply follow a predetermined (recommended) evacuation route under a simple disaster assumption. In other words, the participants are not given opportunities to think about how to evacuate under various disaster assumptions (possible disaster situations). In a real evacuation, people will encounter difficult disaster situations that can obstruct their route to an evacuation site. For example, they will have to choose a safer route by observing their surroundings if a recommended route is destroyed. If they find an injured person, they will have to decide whether to help them. This means that the reality of evacuation drills should be heightened.

To heighten the reality, disaster education has actively been introducing information and communication technology (ICT) such as digital games, artificial intelligence, and virtual reality (VR). For example, Chittaro and Sioni (2015) developed a VR-based serious game where people can learn how to survive terrorist attacks while receiving instructions about proper decisions. Ramchurn et al. (2016) developed a location-based game where disaster responders can be trained to make proper decisions in a radioactive disaster while collaborating with software agents. Radianti et al. (2015) developed a mobile game for training disaster responders that predicts and visualizes a building fire (the spread of smoke and heat) using a Bayesian network. ICT-based evacuation drills (ICTBEDs) have attracted similar attention. For example, Gong et al. (2015) developed a VR-based earthquake evacuation simulator in which people can walk through a three-dimensional virtual world by controlling an avatar with gestures. To increase the degree of reality of evacuation drills, we should focus not only on VR but also on augmented reality (AR), which attaches more importance to the real world. This is because AR can visualize disaster situations realistically by superimposing computer graphics onto a real-time scene (i.e., a person's view).

In this study, our group developed ICTBED systems and conducted ICTBEDs mainly for schoolchildren. Our ICTBED aims at high-reality evacuation drills that result in effective disaster education. The reality can be regarded as a realistic expression of possible disaster situations, i.e., virtual disaster situations (VDSs). Effective disaster education can be regarded as immersive simulated evacuation experiences in which participants make decisions earnestly in VDSs. In a VDS, participants should be able to make some good decisions. Therefore, we think that providing such experiences in an ICTBED can result in effective disaster education. To achieve a high degree of reality, one of our ICTBED systems focused on the combination of AR and a head-mounted display (HMD) (Kawai et al., 2016; Mitsuhara et al., 2016a). To increase the degree of reality further, we used a handheld HMD (i.e., a smartphone-based HMD) to extend this ICTBED system.

2. Disaster Education Model

In disaster-prone countries, disaster education is regularly conducted in various settings (e.g., schools, companies, and communities) but is not fully established yet. A review paper (Johnson, et al., 2014) showed that evaluation methods for disaster education practices (programs) are not unified and it is difficult to discuss the effectiveness of a practice session with objective criteria. Disaster education involves various topics (e.g., geography and psychology) and should be customized to each session (e.g., the target learners). Therefore, we think that more research and practice are required on disaster education. Furthermore, models should be built to help with disaster education.

There is a fundamental disaster management model that consists of four phases: response, recovery, mitigation, and preparedness (NGA, 1979). We believe that disaster education should teach how to respond (e.g., rescue and evacuation) in the preparedness phase (Figure 1).

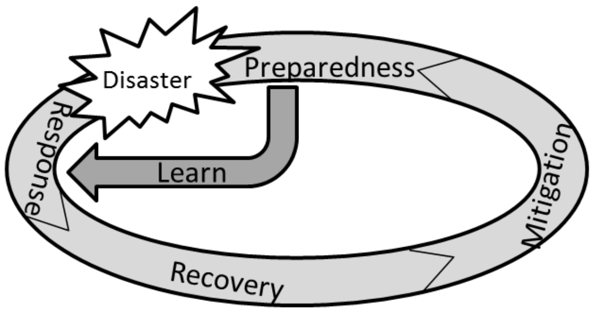


Figure 1. Four-phase disaster management model

2.1 Learning How to Respond

In the response phase (i.e., immediately after a real disaster has occurred), to survive, we must make prompt and correct decisions (and actions). A real disaster is a time for doing rather than learning. In the response phase, we apply what we have learned in the preparedness phase. Therefore, it is important when learning how to respond that we experience such decision-making in virtual disasters, i.e., in simulated experiences.

Simulated experiences are often provided using VR technologies. For example, Bacon et al. (2013) developed a VR-based training system through which strategic planners learn how to make decisions as part of crisis management. This system, which uses artificial intelligence planning techniques and a knowledge base, can control a time-series scenario (i.e., a sequence of events for which the planners must make decisions), taking account of the trainees' abilities and stress levels. Cha et al. (2012) developed a VR-based training system that firefighters can use to learn how to rescue and evacuate victims from a fire in a road tunnel. This system can precisely simulate and visualize the spread of toxic gasses and heat in a virtual tunnel based on fire dynamics data (fluid phenomena prediction).

In this study, we focus not on the disaster responders but on the evacuees (i.e., the public), who can survive a disaster by evacuating successfully. In other words, we explore simulated evacuation experiences.

2.2 The GLI Model

The right decisions in the response phase vary according to the disaster, that is, the when, where, and how. Therefore, we should learn how to evacuate under various disaster assumptions, and we need an effective disaster education model for continuous learning. We propose the GLI model, which has three stepwise learning layers: global, local, and individual (Figure 2).

2.2.1 Global Layer

This layer deals with basic knowledge about each type of disaster (e.g., terminology, past damage, and safety actions). In this layer, learners are expected to acquire knowledge about as many types of disaster as possible. The knowledge will be delivered through various kind of learning material.

2.2.2 Local Layer

This layer deals with the disaster risks in each learner's communities (e.g., residence and school). In this layer, learners who acquired knowledge in the global layer are expected to recognize the disaster risks (e.g., collapsed buildings) through investigative learning (e.g., fieldwork). This kind of learning can be regarded as authentic learning.

2.2.3 Individual Layer

This layer deals with the responses that depend on each learner's individualized assumptions of what might happen and what they can do in a disaster in their local environment. For example, their responses depend on their physical capacity and the health of family members. A learner will make such assumptions based on their perception of possible disaster situations. In this layer, learners who have recognized the disaster risks in the local layer are expected to plan how to survive (evacuate) based on their own assumptions. Evacuation drills should follow the evacuation plans and be based on the knowledge gained in the two higher layers. People will be able to make prompt and correct decisions in a real evacuation if they continue to learn in this layer (i.e., make evacuation plans for many different assumptions).

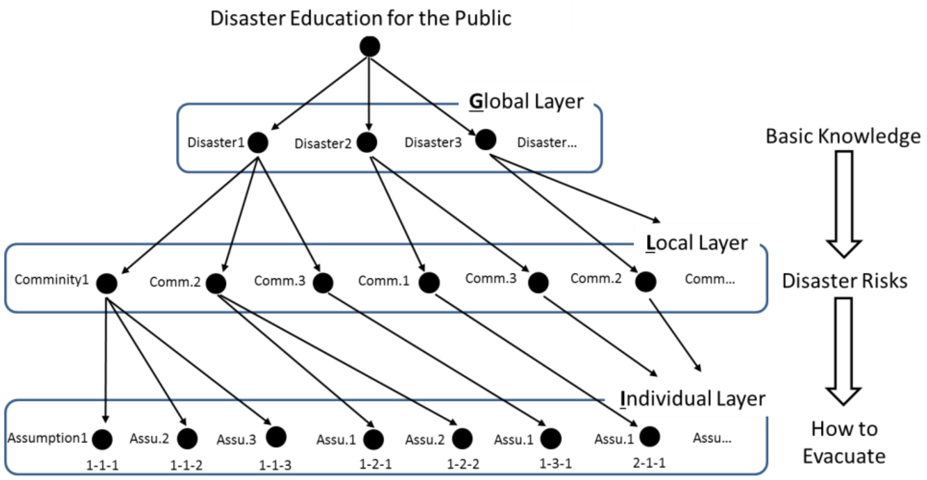


Figure 2. GLI model of disaster education

3. ICT-based Evacuation Drill

It may be difficult for learners to imagine possible disaster situations and to make their individualized disaster assumptions. Due to such difficulties, the reality of an evacuation drill may be lessened. To enhance the degree of reality, their imagination should be complemented. Our group has proposed ICTBED, which aims to complement people's imagination and we developed ICTBED systems.

3.1 Overview

Our ICTBED introduces an interactive disaster scenario (IDS) and digital materials (DM) that express VDSs. The IDS, which begins at specific locations and ends at designated evacuation sites within a time limit, can be regarded as a set of story-based disaster assumptions. It has the following scenes:

- Stay scene (SS): Each SS corresponds to a location designated by a rectangle.
- Move scene (MS): Each MS, conceptually assigned between SSs, prompts participants to reach the next SS.
- Interrupt scene (IS): Each IS is independent of the location and corresponds to the elapsed time or a designated time.

Each scene has at least one cut, which is a unit used to present DM (e.g., a video, slideshow, single-choice question, and AR). The IDS can branch according to the following conditions:

- Option selected (cut to cut): The next cut depends on which option a participant selects.
- Already visited (cut/SS to cut/MS): The next cut/scene depends on which cut/scene a participant has visited in/till the current scene.
- Visited (MS to SS): This condition is valid only for an MS where one or more SSs are candidates for the next scene. After visiting one of the candidates, a participant moves to the next candidate SS for the MS.
- Elapsed time (MS to IS): When the time allocated to a scene reaches a threshold, the participant is forced to visit (jump to) an IS. The participant returns from the forced scene to the previous scene or a designated scene.

The branched IDS enables participants to make decisions in the VDS. In other words, the branched IDS controls the storyline of an evacuation drill according to the learner's decisions (Figure 3), and multiple endings are available. For example, if a recommended evacuation route is destroyed in a VDS, a participant must choose a safer detour for a successful evacuation.

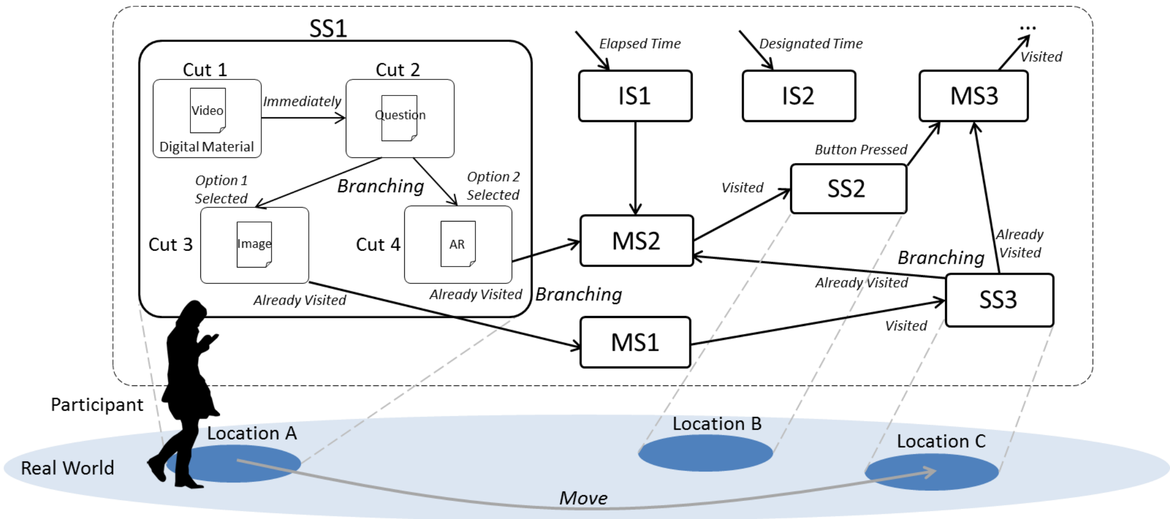


Figure 3. Branched IDS

3.2 ICTBED System

Our group developed three types of ICTBED system (Figure 4). The systems were different in terms of working platform (devices):

- Mobile system (app): This system, which works on GPS-enabled smartphones or tablets, recognizes a participant’s current location and presents DM corresponding to the location (Mitsuhara et al., 2015). In other words, this system is suitable for outdoor ICTBED. An extended version of this system can present AR that visualizes disaster situations by superimposing two-dimensional computer graphics on the real-time view (Mitsuhara, et al., 2013).
- Web system: This system, which works on standard web browsers, enables participants to evacuate in a semi-virtual world using Google Street View (Mitsuhara et al., 2016b). When using this system, the participants do not have to move in the real world.
- HMD system: This system, which works on relatively high-performance laptop computers, requires participants to wear an immersive HMD (Oculus Rift with Ovrvision). It can be used for very real evacuation drills by presenting AR as DM (Kawai et al., 2016; Mitsuhara et al., 2016a). This system is mainly useful for short-range evacuation drills because it is difficult for the participants to move in the real world while wearing the HMD.

Figure 4. Three types of ICTBED system

3.3 AR in ICTBED

The HMD system, which basically recognizes SSs using marker-based AR techniques or GPS, presents AR corresponding to the recognized SS. For the marker-based AR, fiducial markers must be placed at SSs (designated locations) in the real world. Markerless AR is also available; however, it is limited to a few disaster situations (e.g., fog, rain, or shaking). To visualize disaster situations realistically, the HMD system adopts a game engine (Unity 3D) and presents AR that superimposes three-dimensional computer graphics (3DCG) onto the real-time view.

For AR, the visual reality of the HMD system was higher than that of the mobile system. However, most of the ICTBED participants who wore the HMD during preliminary experiments suffered from so-called VR sickness caused by temporal gaps between the presented AR and their visual sense. In addition, assistants had to accompany the participants for operational safety so that staff were needed. Our group considers that ICTBED using the HMD system is still impractical for disaster education due to these negative aspects.

4. Handheld HMD-based AR in ICTBED

To make a practical HMD system, we used a handheld HMD (HHMD) consisting of a smartphone in a lightweight frame made of plastic or cardboard. The HHMD is easy for participants to wear (hold to their eyes) and take off during evacuation drills. The participants can take off the HHMD and move during MSs to prevent VR sickness. This device make it easier conduct ICTBED without assistants. We prototyped the HHMD system as an extended version of the HMD system.

4.1 Implementation

Currently, the HHMD system recognizes SSs using marker-based AR techniques, focusing on indoor evacuation drills (e.g., earthquake evacuation drills where participants escape from a building to the outside). This is because printed fiducial markers are occasionally difficult to use outside due to rain, wind, etc.

The HHMD system works on relatively high-spec Android smartphones and the AR is implemented using a game engine (Unity 3D) and a marker-based AR software development kit (Vuforia). The latest version of Vuforia can deal with markerless AR. For the HHMD system, basically, a fiducial marker is prepared for each disaster situation. The same marker can be reused if an IDS has a linear storyline (without branches). The HHMD system presents AR via the following steps:

i. It captures the fiducial marker with the real-time vision at an MS.
ii. It recognizes the next SS by checking the captured marker based on the IDS. If the captured marker does not match any of the SS candidates, the corresponding SS is not recognized as the next SS.
iii. It presents AR corresponding to the recognized SS (as DM at the first cut). In other words, it superimposes the corresponding 3DCG onto the real-time view.
iv. It adjusts the position of the superimposed 3DCG synchronously based on the direction in which the participant is looking (i.e., the direction in which the smartphone's rear camera is pointing) using the extended tracking function provided by Vuforia.

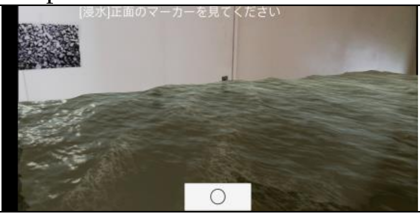
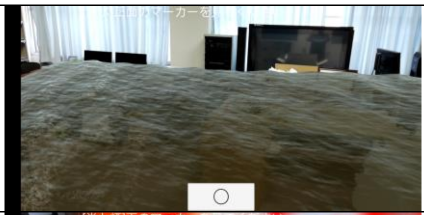
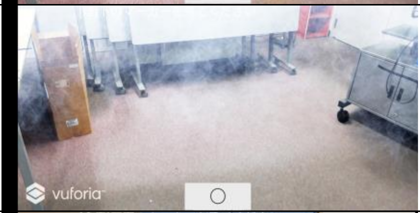
4.2 AR Examples

In MSs, the participants can take off the HHMD and move in the real world (building) to find a fiducial marker. On finding a marker, they gaze at it through the HHMD until the corresponding AR is presented. Currently, the HHMD system presents AR that visualizes seven earthquake-related situations (Table 1).

As long as the participants view the presented AR by moving the HHMD slowly, the HHMD system can maintain the positional consistency of the superimposed 3DCG correctly. For example, they can view water as if it were spread all around the space (Table 1-I). Fire and smoke are rendered with the particle system provided by Unity 3D. On approaching a rendered fire (i.e., the corresponding marker), the participants will see an enlarged fire (Table 1-II). If they look up at the ceiling, they will see thick smoke (Table 1-III). Animation and sound can be added to the AR. For example, when an afterquake occurs, the participants can see and hear a cracked window breaking (Table 1-IV).

Table 1

AR examples that visualize earthquake-related situations

Disaster situation	Snapshot	
I Water (tsunami)		
II Fire		
III Smoke		
IV Cracked and broken window		
V Crack (in the floor)		
VI Collapsed wall		
VII Injured person		

4.3 Preliminary ICTBED Experiment Using the HHMD System

We used the HHMD system to conduct a preliminary ICTBED experiment. The scenario was an earthquake evacuation (a first-step escape from a damaged room into a corridor) at an educational event for children (elementary and junior high school students) to examine whether participants accepted the ICTBED (Figure 4).

4.3.1 Settings

In this experiment, a small simple maze was built in a room and the participants were required to reach the end within 5 minutes while making decisions against the seven VDSs (shown in Table 1). Almost all of the participants moved in the maze while wearing the HHMD even though they could take off it. However, due to operational reasons, this experiment was conducted differently than the expected ICTBED:

- Although the HHMD system was designed to be used by the participants themselves (i.e., without assistants), assistants accompanied the participants (children) to make the learning more effective and for operational safety. We thought that the assistants should have the flexibility to give the participants instructions about how to make decisions in the VDSs and occasionally guide them to the end.
- The participants' decision-making was limited to whether to take shortcuts that could be dangerous due to a fire, a crack, or a collapsed wall. Just as we intended, none of them took the shortcuts. For the other VDSs, the participants simply viewed the presented AR and were asked by the assistants about possible correct decisions in the VDS. For example:
  - Assistant: "What should you do when you find an injured person who is heavier than you?"
  - Participant: "I want to help him, but I cannot carry him. So, I should cry out to adults for help."
  - Assistant: "That's a good idea, but there are no adults nearby. In this case, let's leave him and continue to evacuate to protect your life."

Figure 4. Snapshots of preliminary experiment

4.3.2 Results

We conducted a questionnaire survey immediately after each participant reached the end. Table 2 summarizes the questionnaire results for the elementary and junior high school students ($n = 192$). Concerning the reality of the presented AR (Q1), about 90% of the participants replied "yes." The participants tended to feel that the water, smoke, injured person, and broken window were realistic. Some participants said that the broken window was most realistic due to the breaking sound. A few participants stepped away from the real window at the SS. From these results, we think that the presented AR can visualize VDSs realistically. Concerning the participants' fear caused by the presented AR (Q2), the mean value was 3.55 but 41 participants replied "disagree" or "strongly disagree." Although the ICTBED does not necessarily aim to produce scary simulated experiences, we feel positive about the mean value because their fear seems to be due to the reality. Concerning their enjoyment of the ICTBED (Q3), the mean value was 4.48 and about 90% of the participants replied "agree" or "strongly agree." In spite of feeling fear, many of the participants enjoyed the ICTBED. Concerning their disaster awareness (Q4), the mean value was 4.18 and we think that the ICTBED can provide the minimum level of learning (increased awareness) as practical disaster education. Concerning their sustainable motivation for the ICTBED (Q5), the mean value was 4.33 and almost all the participants replied positively.

From the above results, we conclude that the ICTBED using the HHMD system was accepted by the participants. In addition, we believe that the ICTBED can provide very real simulated evacuation experiences that entail enjoyment and learning effectiveness.

Table 2

Questionnaire results

Question	Reply
Q1 Is the presented AR (disaster situations) realistic? Yes/No Which ARs are realistic?	Yes=172, No=17
	Mean (standard deviation)
Q2 Is the presented AR scary?	3.55 (1.25)
Q3 Is this evacuation drill enjoyable?	4.48 (0.73)
Q4 Has your disaster awareness increased?	4.18 (0.80)
Q5 Would you like to participate in this evacuation drill (e.g., as a class in your school)?	4.33 (0.83)

Answers: 1 strongly disagree, 2 disagree, 3 neutral, 4 agree, 5 strongly agree

4.3.3 Limitations

This experiment had limitations. Since it was possible that children in the lower grades of elementary school replied without understanding the questions (especially about the reality), the reliability of the questionnaire survey may be insufficient. In this experiment, the HHMD system did not use a branched IDS, i.e., the storyline did not change according to their decisions. In addition, the participants were not given enough opportunities to reflect on the evacuation. These limitations mean that this experiment did not sufficiently evaluate whether the ICTBED taught the children how to evacuate.

5. Conclusions

This paper described an ICTBED system that combined AR and HHMD to heighten the reality of evacuation drills. The HHMD system (an extended version of an HMD system), which aims to make the HMD system practical, presents marker-based AR on a HHMD. The AR visualizes disaster situations realistically by superimposing 3DCG on the real-time view. The preliminary experiment showed that the ICTBED can provide very real simulated evacuation experiences. However, we have not evaluated sufficiently whether the ICTBED can be useful as practical disaster education.

With the spread of high-spec smartphones, mobile AR has been attracting attention for disaster education. For example, Dong et al. (2016) developed a mobile AR-based system that trains first responders to assess disaster situations adequately and plan responses. This system realizes markerless AR by superimposing 3DCG of disaster situations (e.g., fire, tornados, and injured people) on the real-time view using a smartphone’s GPS, electronic compass, and disaster scenarios. Itamiya (2017) developed a mobile AR-based system that visualizes floods and smoke realistically using markerless AR technology (Google Tango) and smartphone-based HMDs. Like these examples, the advances in AR technology will accelerate the development of disaster education including ICTBED.

We continue to extend our HHMD system to make ICTBED more effective as practical disaster education. For example, the HHMD system should realize AR that visualizes more disaster situations and be easily available (set up) by the public (e.g., schoolteachers). In addition, we want to understand how best to learn how to evacuate using a HHMD system.

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