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Game-based evacuation drill using augmented reality and head-mounted display

Abstract

Purpose–Evacuation drills should be more realistic and interactive. Focusing on situational and audio-visual realities and scenario-based interactivity, we have developed a game-based evacuation drill (GBED) system that presents augmented reality (AR) materials on tablet computers. Our current research purpose is to improve visual reality (AR materials) in our GBED system.

Design/methodology/approach–Our approach is to develop a new GBED system that superimposes digital objects (e.g. 3DCG elements) onto real-time vision using a marker-based AR library, a binocular opaque head-mounted display (HMD) and other current easily available technologies.

Findings–Our findings from a trial experiment are that the new GBED system can improve visual reality and is appropriate for disaster education. However, a few problems remain for practical use.

Research limitations/implications–When using the GBED system, participants (i.e. HMD wearers) can suffer from 3D sickness and have difficulty in moving. These are important safety problems in HMD-based systems.

Social implications–The combination of AR and HMDs for GBEDs (i.e. integrating virtual and real worlds) will raise questions about its merits (pros and cons).

Originality/value–The originality of our research is the combination of AR and an HMD to a GBED, which have previously been realized primarily as simulation games in virtual worlds. We believe that our research has the potential to expand disaster education.

Keywords Augmented Reality, Head-mounted Display, Reality, Interactivity, Game-based Education, Evacuation Drill, Disaster Education

1. Introduction

The research field of ‘game-based education’ (GBE), dubbed ‘edutainment’ or ‘serious games’, has been attracting significant attention (Connolly et al., 2012; Girard et al., 2013). GBE increases learning motivation and effect by making learning fun through game elements (gaming technologies). There have been various GBE systems, such as an adventure game for teaching intercultural business communication (Guillén-Nieto & Aleson-Carbonell, 2012), a board game with pedagogical agents for teaching mathematics (Takaoka et al., 2012) and a competitive quiz game in social media for teaching climate change (Seebauer, 2014). These systems provide learners with enjoyable digital materials (i.e. virtual game worlds).

Nowadays, learners can view digital materials anywhere, because mobile computers (e.g. smartphones and tablet computers) have spread. Accordingly, virtual game worlds and the real world are being integrated in GBE. This integration can provide learning through field activities. For example, Klopfer and Squire (2008) developed a story-based game that furnishes students with scientific argumentation skills. In this game, learners role-play environmental detectives and identify the source of a pollutant by receiving fictitious location-based environmental data and advisory messages from virtual characters. In museums and zoos, quizzes and puzzles that are related to exhibitions (Ghiani et al., 2009) and animals (Sandberg et al., 2011) are presented to visitors. These systems use a global positioning system (GPS) or radio frequency identification (RFID) to recognize locations or real-world objects.

We previously considered applying the abovementioned integration to evacuation drills. Evacuation drills, which can be considered field-based simulation experiences, encourage participants (learners) to think about how to survive natural disasters; thus, such drills are important for disaster education and common in schools, companies and communities. However, conventional evacuation drills are monotonous and insufficient. Participants simply follow fixed evacuation routes and are unmotivated to learn about disaster response. During a real evacuation, evacuees may encounter serious situations and may have to make various decisions. Therefore, we thought that evacuation drills should be more realistic and interactive. As a result, we developed a game-based evacuation drill (GBED) system that focuses on situational and audio-visual realities and scenario-based interactivity (Mitsuhara et al., 2013).

The GBED system was derived from the Real-world Edutainment (RWE) program, which is a location-based educational game (similar to role-playing or adventure games) that uses a tablet computer with a GPS receiver, an RFID reader, an electronic compass and a small camera (Noda et al., 2010). The GBED system presents digital materials (e.g. images, videos and single-choice questions) based on a participant's current circumstances (e.g. location) and a branched evacuation scenario (game storyline). In the evacuation scenario, it is important to create very realistic situations. In other words, situational reality must be considered. The digital materials represent serious disaster situations that correspond to locations. In addition, it is important to make disaster situations more realistic using audio-visual effects, i.e. auditory-visual reality must also be considered.

We conducted the GBED at several schools for a subduction-zone earthquake (Figure 1). Participants were required to get to the evacuation sites (higher elevations) no later than a tsunami event. Through a questionnaire survey, we determined that the GBED improved student motivation for disaster response; however, visual reality was insufficient, because the digital materials did not adapt visually to real-time situations (e.g. weather and hours).

To improve visual reality, we adopted markerless augmented reality (AR) as a new digital material in the GBED system. The AR material superimposes a background-transparent image onto the real-time vision captured by the tablet computer's camera. We experimented with the AR materials in a small-scale evacuation drill and found through a questionnaire that visual reality was still insufficient, because presentation of the AR material was not stable and the tablet computer's screen was not large enough.

From this background, we have developed a new GBED system that uses a marker-based AR library for stable presentation and a binocular opaque head-mounted display (HMD) as a replacement for the tablet computer.

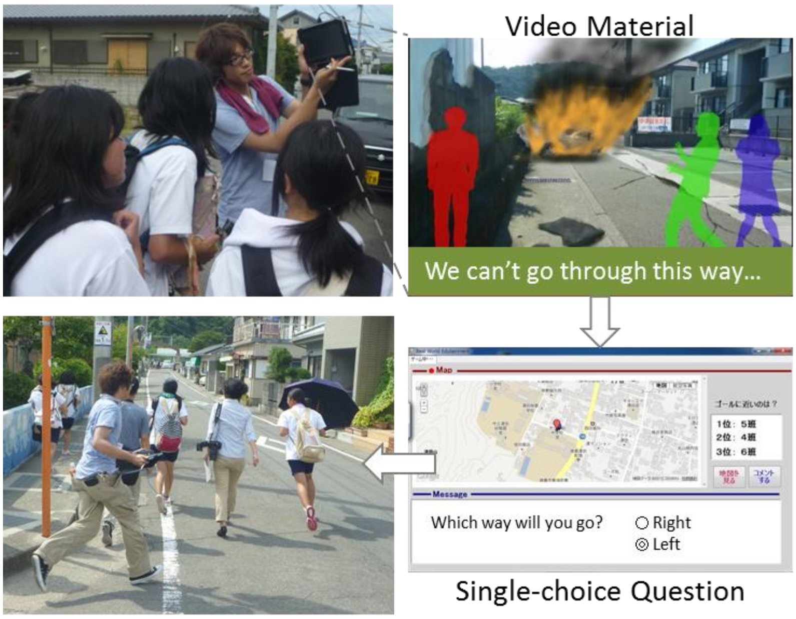


Figure 1. Snapshots and digital materials in the GBED

2. Game-based Evacuation Drill using Real-World Edutainment

Our primary idea is that the game elements in RWE can motivate a wide range of people to participate in evacuation drills. In the GBED, an evacuation scenario begins at a certain location and ends at a designated evacuation site within a time limit. Participants experience pseudo disaster situations in a race against time scenario that involves consecutive decision-making (i.e. the game elements).

2.1 Evacuation Scenario

Natural disasters often cause moral dilemmas, such as life-saving and safety-promoting actions that go against the principle of 'a speedy escape'. Therefore, to make a participant think seriously about disaster response, the evacuation scenario should deal with realistic situations that consider moral dilemmas. Difficult decisions that must be made between multiple right choices are often treated as subjects in GBE (Zagal, 2009). For example, when digital materials that represent an encounter with an injured person are presented at a given location, a participant must answer a yes-no question, 'Will you help the injured person?' If they answer 'yes', the participant must give first aid to the injured person played by a real human actor while referencing digital materials about first-aid methods.

The GBED system recognizes a participant's current location and presents corresponding digital materials based on the recognized location and the given evacuation scenario. The evacuation scenario (described in XML) is composed of scenes and cuts (Figure 2). The scenes are categorized into 'stay' scenes (SSs), 'move' scenes (MSs) and 'interrupt' scenes (ISs). Each SS corresponds to a location and is composed of at least one cut. MSs and ISs are independent of location and are conceptually located between SSs. A cut is the smallest unit used to present digital material.

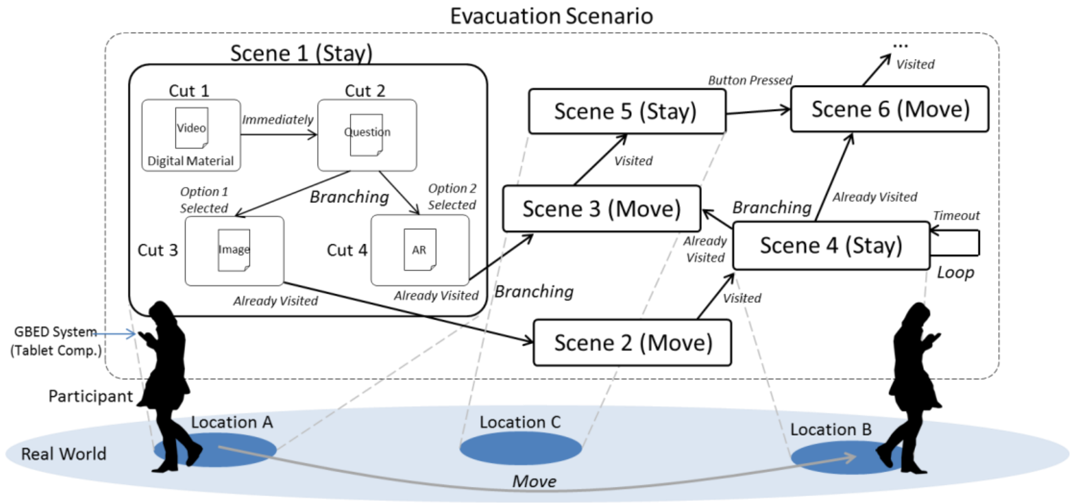


Figure 2. Branched evacuation scenario in the GBED

2.2 AR Material

The GBED system recognizes an SS and presents the AR material that corresponds to a cut in the SS by superimposing a background-transparent image onto the real-time vision captured by the tablet computer's camera (Figure 3). The AR material is presented according to the following procedure.

(1) *Similarity Calculation*

To begin AR material presentation, the GBED system calculates the brightness similarity between the real-time vision and a previously shot image using the sum of absolute differences.

(2) *Superimposing*

The GBED system superimposes a designated image onto a designated position in the real-time vision as soon as the calculated similarity is less than a threshold.

(3) Synchronization

To synchronize the superimposed image with the real-time vision, the GBED system adjusts the image's position at millisecond intervals using Optical Flow, which extracts the motion vectors between two successive frames in the real-time vision.

Figure 3. AR material presentation

The GBED system had difficulties with AR material presentation due to instability (low robustness) of the similarity calculation and synchronization. In addition, the tablet computer's screen was too small to view the details of the AR material and was difficult to view due to surface reflection from the Sun. These difficulties reduced visual reality.

3. Augmented Reality and Head-Mounted Display

The goal of our current research is to improve visual reality in the GBED system. To achieve this, we have attempted to increase the stability of AR and have employed an HMD with a wide field of view. In addition, we have adopted a marker-based AR library and a binocular opaque HMD (video see-through HMD).

3.1 Related Work

AR has been actively introduced into education, and there have been various educational AR systems (Cheng & Tsau, 2013) (Santos et al., 2014). For in-classroom education, AR materials are presented on handheld displays (Billinghurst et al., 2001), desktop displays (Di Serio et al., 2012) or tabletops (Cuendet et al., 2013). For field-based education, AR materials are often presented on mobile computers, such as PDAs (Wagner et al., 2006) and smartphones (Redondo et al., 2013). A location-based educational AR system superimposes text adapted to each learner's profile and status onto the real-time vision (Tan et al., 2015). In field-based education, the concept of AR (i.e. AR material presentation) has been diversified. For example, some systems advocating AR recognize locations or real-world objects using GPS (Kamarainen et al., 2013), quick response codes (Bressler & Bodzin, 2013) or image recognition techniques (Chang et al., 2015), but do not have superimposing functions. Such systems present digital materials asynchronously with the real-time vision. Although diversified concepts (AR material presentation methods) are available for some subjects, superimposing functions are indispensable for effective disaster education and improving visual reality in the GBED system.

Research into the combination of AR and HMDs has a long history. For example, a guide system provides users with information about university campuses using text-based AR and an optical see-through HMD (Feiner et al., 1997). This combination has also been introduced in education. For example, manipulatable 3DCG of Earth–Sun relationships in geography (Shelton & Hedley, 2002) and curves in geometry (Kaufmann & Dünser, 2007) are superimposed onto real-time vision using video and optical see-through HMDs. In music education, virtual notes are superimposed onto physical piano keys so that beginners can become accustomed to playing the piano (Chow et al., 2013). These systems deal with subjects that do not require the wearers (learners) of the HMDs to make extensive movements, because they reduce awareness of surroundings and it is difficult to move around safely.

On the other hand, evacuation drills require that participants make extensive movements (widespread migration). If the participants wear HMDs and move, they may fall. HMDs may prevent them from simulating a speedy escape. However, in a real evacuation, an evacuee may not accomplish a speedy escape by encountering difficulties (serious disaster situations). Therefore, we believe that evacuation drills should involve various difficulties, and the combination of AR and HMDs can emphasize such difficulties by improving the situational and visual realities. Note that miniaturized HMDs, dubbed 'smart glasses', are expected as wearable devices for education. For example, an inquiry-based learning system is designed with Google Glass, which provides hands-free interaction (voice interaction) and allows users to make instant inquiries (Suarez et al., 2015). The miniaturized HMDs do not appear to prevent speedy escape, but will not improve visual reality, because their viewing angles (i.e. the perceived display sizes) are narrow. Therefore, we adopt a binocular opaque HMD with a wide viewing angle.

In the past, GBEDs have been realized primarily as simulation games in virtual worlds. For example, a simulation game about fire evacuation allows learners to evacuate from a virtual 3D building (Dunwell et al., 2011). Other simulation games have realized virtual fire evacuation using a public 3D viewing space (Smith & Ericson, 2009), HMDs and other platforms (Wang et al., 2014). Such GBEDs are sufficient for safer disaster education, but are insufficient for more realistic disaster education. In an evacuation drill in a virtual world, it is difficult for participants to realistically feel the surrounding environment, psychological pressures and physical tiredness. In contrast, in real-world evacuation drills, it is difficult for participants to engage in disaster situations because such drills are conducted under safe simulated conditions (e.g. fixed evacuation routes without any obstacles). Therefore, we think that the new GBED system (i.e. more realistic evacuation drills by integration of virtual and real worlds) is necessary for disaster education.

3.2 System Overview

The new GBED system, extended from the previous GBED system, uses the latest easily available technologies (Table 1) to improve visual reality.

Table 1. Technologies used in the new GBED system

Technology (product)	**Overview**
ArUco	ArUco is a maker-based AR library compatible with Unity 3D and Ovrvision.
Oculus Rift	Oculus Rift is a binocular opaque HMD that provides high immersion due to its 110-degree viewing angle and sensitive head motion tracking.
Unity 3D	Unity 3D is a cross-platform game engine for introducing 3DCG, auditory-visual effects and other gaming representations.
Ovrvison	Ovrvision is a small stereo camera attachable to Oculus Rift.

The new GBED system, which works on relatively high-performance mobile computers with Oculus Rift and Ovrvision, uses ArUco to recognize SSs and cuts to present the corresponding AR materials through fiducial marker recognition, superimposing and synchronization (Figure 4). Note that fiducial markers associated with SSs and cuts must be set in the real world.

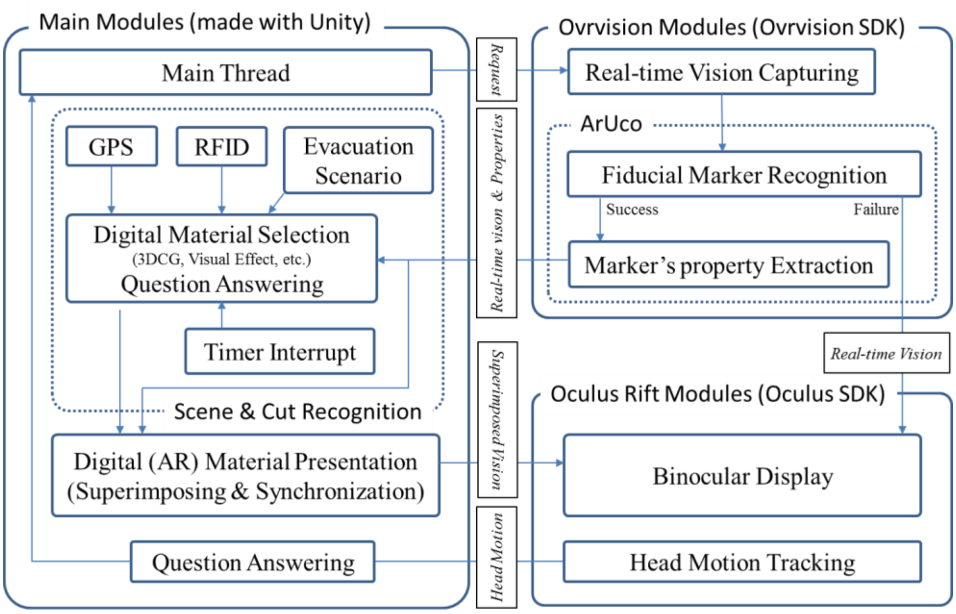


Figure 4: System overview (modules and processing)

In the new system, digital objects to be superimposed onto the real-time vision include text, images, videos and single-choice questions, as well as 3DCG elements and visual effects that represent serious disaster situations with high visual reality (Table 2). The 3DCG elements and visual effects are categorized into position-sensitive superimposing and overall superimposing depending on whether fiducial markers are required. The above-mentioned technologies for AR material presentation allow participants to perceive depth-inclusive omnidirectional space, which improves visual reality.

Table 2. Principal disaster situations and corresponding digital objects

Superimposing 3DCGs or visual effects onto the real-time vision			
Disaster situation	**Marker**	**Digital objects (implementation)**	**Example**
Fire	Yes	Dynamic rendering by the Unity 3D's Particle System	
Injured person	Yes	Predefined 3D model or predefined image	
Crack	Yes	Predefined 3D mode or predefined image	

Smoke	Yes/No	Particle System, predefined 3D mode or predefined image	
Rain	No	Particle System	
Fog	No	Particle System	
Arranging the real-time vision			
Disaster situation	**Marker**	**Implementation**	**Intended use**
Darkness	No	Contrast change of the real-time vision	Evacuation in dark situations (e.g. blackout and the inside of a collapsed building)
Shake	No	Shake of the real-time vision	Earthquake, impulsion and giddiness

3.2 AR Material Presentation

(1) Fiducial Marker Recognition

To recognize fiducial markers, the new system searches the real-time vision (each frame) captured by Ovrvision for predefined markers and extracts marker properties (e.g. position, size and angle).

(2) Superimposing

The new system superimposes digital objects that correspond to the recognized markers onto the real-time vision according to the initial values of the objects' properties.

(3) Synchronization

At millisecond intervals, the new system synchronizes the superimposed objects with the real-time vison by adjusting the objects' properties according to the extracted markers' properties.

3.3 AR Material Settings

For the AR material presentation, the relationships between fiducial markers and digital objects must be set in each evacuation scenario. ArUco includes 1,024 fiducial markers with unique IDs that can be linked with the digital objects controlled by Unity 3D. For high visual reality, it is most important to maintain geometric, photometric and time consistencies between the superimposed objects (virtual world) and real-time vision (real world). Currently, the new system aims to maintain only geometric consistency (i.e. position, size and angle) by manually optimizing the initial values of the superimposed objects' properties. The new system provides a tool that enables evacuation scenario designers to adjust the initial values while viewing the superimposed objects through Oculus Rift in the actual field. The AR material settings are described in the evacuation scenario, as shown in the following example.

```
<scene no="1" type="stay" id="101">
    <name>An injured person</name>
    <condition sensor="gps" method="rectangle">34.042036,134.577465,34.041818,134.577632</condition>
    <cut no="1" id="1001">
        <bgm loop="false">ohmygoodness.wav</bgm>
        <message>Look at an AR marker around you.</message>
        <next condition="button_pressed">2</next>
    </cut>
    <cut no="2" id="1015">
        <content type="AR" marker="1" size="1.0" roll="-1.0" pitch="0.5" yaw="1.0" >injured01.unity3d</content>
        <next condition="button_pressed">3</next>
    </cut>
    <cut no="3" id="1018">
        <message>Will you rescue the injured person?</message>
        <content type="ask" second="0">
            <option id="1" score="0">Yes</option>
            <option id="2" score="0">No</option>
        </content>
        <next condition="option_selected" value="1">4</next>
        <next condition="option_selected" value="2">5</next>
    </cut>
    <cut no="4" id="1022">
        <message>Watch your steps!</message>
        <content type="AR" marker="2" size="2.0" second="30">crack.jpeg</content>
```

```
                <next condition="end" />
        </cut>
        <cut no="5" id="1216">
                <message>Fire is coming!</message>
                <content type="vfx" strength="0.8" second="15">fire</content>
                <next condition="immediately">6</next>
        </cut>
        <cut no="6" id="1512">
                <message>Let's go to another place!</message>
                <content type="vfx" strength="1.0">smoke</content>
                <next condition="end" />
        </cut>
        <next condition="already_visited" cut="4">2</next>
        <next condition="already_visited" cut="6">3</next>
</scene>
```

3.4 Scenario-based Interactivity

The new system branches an evacuation scenario according to a participant's answers to single-choice questions. However, it is difficult for participants wearing Oculus Rift to answer the questions through conventional methods (e.g. keyboard, mouse and touch operations). Therefore, the new system provides two methods that enable the participants to answer by eye direction (Figure 5). In the method using fiducial markers, they can answer by gazing at one of the markers associated with choices for several seconds. In the method using head motion tracking (Oculus Rift), they can answer by gazing at one of the designated directions associated with choices for several seconds.

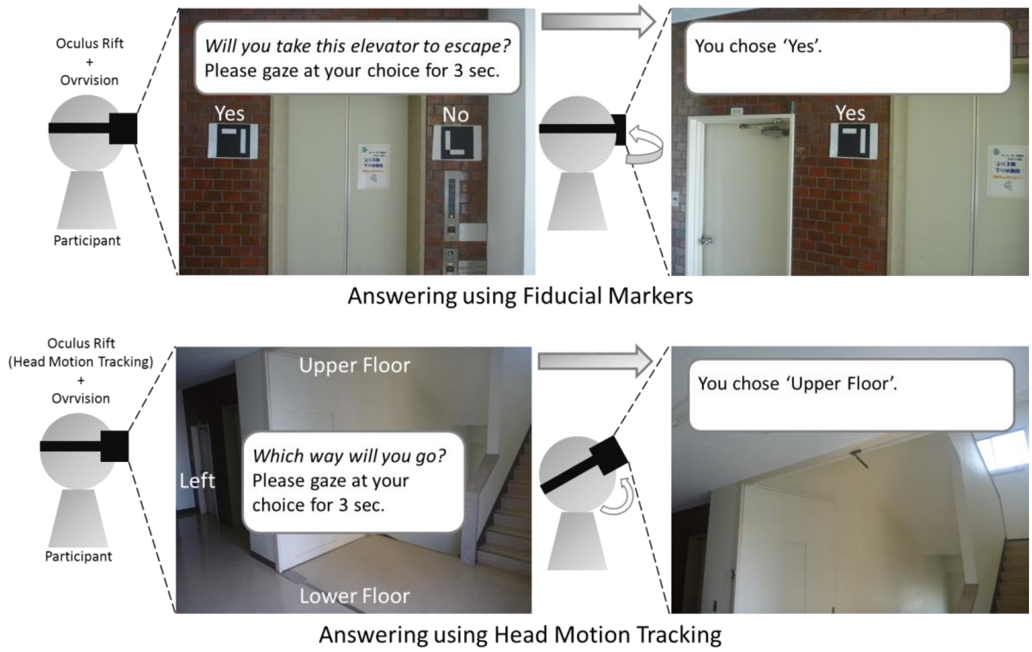


Figure 5. Answering methods based on eye direction

4. Trial Experiment

We conducted a small-scale evacuation drill as a trial experiment using the new GBED system. The subjects were 17 high school students who participated in a campus tour of Tokushima University. For safety reasons, participants wearing Oculus Rift (with Ovrvision) indoors were accompanied by an assistant who helped them move and gave minimal instructions while holding the computer (Figure 6).

In this experiment, the new system recognized SSs and cuts using fiducial markers and superimposed the corresponding digital objects onto the real-time vision. The digital objects included 3DCG elements specific to the evacuation drill field (a building on the campus).

Figure 6. Snapshots from the trial experiment

4.1 Evacuation Scenario

The evacuation scenario assumed that campus visitors (high school students) experienced a big earthquake in a five-story building on the campus. The visitors had to evacuate from the fifth floor to outside the building within approximately 15 min. The principal SSs are listed in sequential order as follows.

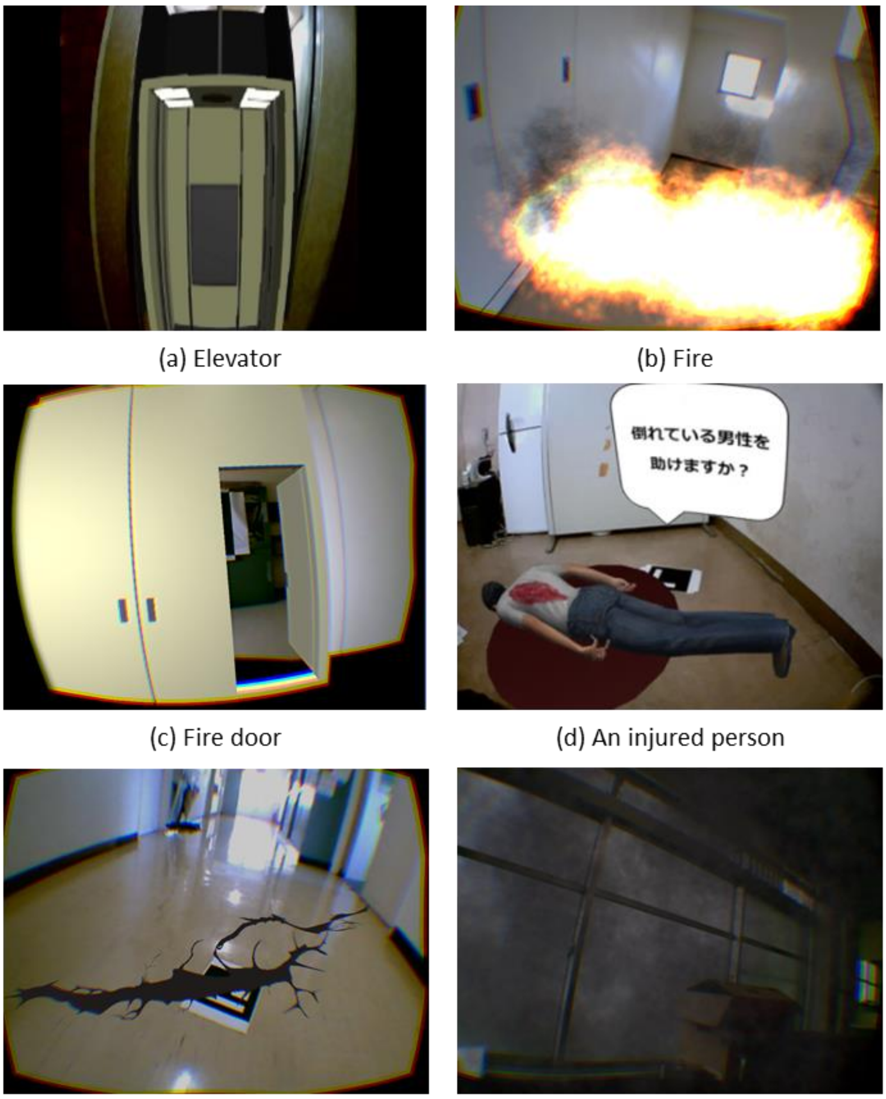
i. Emergency earthquake alert sounds. After several seconds, the big earthquake occurs (seismic intensity 6 upper) and intensive shaking continues for 1 min. During this period, the 'shake' visual effect is active. Then, a visitor (only one survivor) listens to an evacuation directive and begins evacuation from the fifth floor.
ii. The visitor chooses whether to take an elevator or stairs. At this time, a single-choice question is presented. If the elevator is chosen, the elevator car falls immediately before they attempt to enter it. For safe evacuation, the stairs should be chosen (Figure 7-a).
iii. While going down the stairs, the visitor encounters fire and is forced to go back to an upper floor (Figure 7-b).
iv. The visitor is confronted by a fire door and opens the door to reach another staircase (Figure 7-c).
v. The visitor finds an injured person and chooses whether to rescue them (Figure 7-d). If the rescue is chosen, they must evacuate while holding a real weight (an 8 kg doll) representing

the injured person.

vi. The visitor finds cracks on the floor and chooses whether to jump over the cracks (Figure 7-e). If the jump is chosen, they must evacuate with a real weight (a 1 kg ankle weight) representing an injury incurred when jumping.

vii. The visitor leaves the smoke-filled building and completes the evacuation (Figure 7-f).

This scenario included two ISs, ‘afterquake’ and ‘building collapse’ (time’s up), which occurred 7 and 15 min, respectively, after the start of their evacuation. At the former IS, the ‘shake’ visual effect was active for 30 s. At the latter IS, the ‘darkness’ visual effect was active and the final announcement (evacuation failure) was played.



(a) Elevator (b) Fire

(c) Fire door (d) An injured person

(e) Cracks (f) Smoke-filled building

Figure 7. AR materials in the trial experiment

4.4 Questionnaire Survey

We conducted pre- and post-trial questionnaires (5-degree questions and free descriptions) to determine the comprehensive availability of the new GBED system. For the pre-trial questionnaire (Table 3), all mean values were 2.5 or less, which indicates that the participants found conventional evacuation drills monotonous and insufficient.

For the post-trial questionnaire (Table 4), all mean values were 3.8 or greater, which indicates that the new GBED system can be superior to conventional evacuation drills. The mean value (4.4) of POST-Q1 may have resulted from both high situational and visual realities in the evacuation scenario and the AR materials. The mean value (4.2) of POST-Q6, which asked about visual reality (the AR materials) directly, may have resulted from the superimposed 3DCG elements. Through the free descriptions, many of the participants said that they were impressed by the realistic representation of the fire and the fire door. The 3DCG human (the injured person superimposed onto the real-time vision) may be less realistic than the intangible objects and artefacts. The mean value (3.8) of POST-Q2, which was slightly lower than those for other questions, indicates that the participants (wearing the HMD) could not concentrate on the evacuation due to difficulties with awareness of their surroundings and moving safely. From the mean value (4.3) of POST-Q3, another reason may be that the game element (fun) decreased fear (seriousness). This trade-off between fear and fun, and fear and the difficulties should be addressed. The mean values (4.3 and 4.3) of POST-Q4 and POST-Q5 indicate that the new system motivates participants to learn about disaster response. Overall, from all mean values, we believe that the new system is appropriate for disaster education, because the situational and visual realities have been improved and the realities (learning elements) and fun (game elements) can be supported simultaneously.

Table 3. Pre-trial Questionnaire Results

Question	**Mean**	**SD**
PRE-Q1.Are the conventional evacuation drills realistic?	2.1	0.90
PRE-Q2. Do the conventional evacuation drills evoke fear (seriousness)?	2.1	0.90
PRE-Q3. Are the conventional evacuation drills fun?	2.1	0.90
PRE-Q4. Do the conventional evacuation drills increase your motivation for disaster prevention?	2.5	0.98
PRE-Q5. Do you want to participate in the conventional evacuation drills again?	2.4	0.98

Options: 1= ‘Strongly disagree’, 2=‘Disagree’, 3=‘Neutral’, 4=‘Agree’, 5=‘Strongly agree’

Table 4. Post-trial Questionnaire Results

Question	**Mean**	**SD**
POST-Q1. Is this evacuation (GBED using AR and HMD) drill realistic?	4.4	0.86
POST-Q2. Does this evacuation drill give you fear (seriousness)?	3.8	1.0
POST-Q3. Is this evacuation drill fun?	4.3	1.03
POST-Q4. Does this evacuation drill increase your motivation for disaster prevention?	4.3	0.91
POST-Q5. Do you want to participate in this evacuation drill again?	4.3	0.91
POST-Q6. Is the AR material presented is visually realistic?	4.2	0.80

Options: 1= 'Strongly disagree', 2='Disagree', 3='Neutral', 4='Agree', 5='Strongly agree'

4.5 Problems

Through our observations and the obtained opinions (free descriptions) of this experiment, we found the following problems.

(1) Failure in AR Material Presentation

The fiducial marker recognition and synchronization failed occasionally. A possible failure factor is the marker's size and distance from the HMD. In this experiment, we used 20-cm and 50-cm square markers. The former markers were recognized within approximately 3 m and the latter markers were recognized within approximately 5 m. When AR materials need to be presented at a point distant from fiducial markers, the fiducial markers must be bigger. Another factor is external light. If used outdoors, the new system will be significantly affected by sunlight. If participant action is limited to pivoting on the spot, the synchronization can be performed based on head motion tracking once a fiducial marker is recognized. However, restricting participant actions should be avoided.

(2) 3D Sickness

In this experiment, almost all participants suffered from 3D sickness to some extent due to viewing the real-time vision through the HMD. This was particularly evident with the 'shake' visual effect. 3D sickness is primarily caused by the difference between information obtained by the eyes and other sensory organs. In addition, the mobile computer used in this experiment caused slight latency (delay) when capturing the real-time vision. To minimize latency, higher-performance HMDs (e.g. the next Oculus Rift called 'Crescent Bay'), cameras (e.g. the next Ovrvision called 'Ovrvision Pro') and mobile computers may be necessary. We think that 3D sickness can be reduced by such new devices in addition to our efforts to improve system implementation.

(3) Difficulties in Moving

Although the accompanying assistant successfully helped the participants to move around, they could not always move smoothly. We had assumed this would be true; however, difficulties in moving were more serious than expected. Some participants had to remove the HMD to move, in part due to 3D sickness. Ideally, participants who wear the HMD and a mobile computer (e.g. in a rucksack) should be able to perform the evacuation drill without an assistant. This problem should also be addressed to improve the availability of the new system.

5. Conclusions

In GBEDs, situational and auditory-visual realities should be improved so that participants can be motivated to learn about disaster response. We have developed a new GBED system that uses a marker-based AR library (ArUco) and a binocular opaque HMD (Oculus Rift) to improve the visual reality of the AR materials presented in the GBED. Through a trial experiment, we found that the new system can improve visual reality and motivate participants to learn about disaster response. On the other hand, a few problems remain unresolved. For example, solving 3D sickness and difficulties in moving (i.e. safety problems) are considered high priority for practical application (e.g. in schools) of the new system.

Our research depends heavily on devices. For example, new HMDs are being developed rapidly and wearers may soon be able to view presented materials safely while moving. We would like to wait for new devices that satisfy the requirements of our research. In addition, even though HMDs impede learner mobility, we insist that our research is necessary for effective disaster education. However, we must clarify the effectiveness of the new system through many large-scale practical experiments.

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