Master's Thesis

Compelling AR Earthquake Simulation with AR Screen Shaking

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Submitted on July 31, 2021

A Master's Thesis
submitted to Graduate School of Science and Technology,
Nara Institute of Science and Technology
in partial fulfillment of the requirements for the degree of
MASTER of ENGINEERING

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Abstract

Many countries around the world suffer losses from earthquake disasters. To reduce the injury of individuals, safety training is essential to raise people's preparedness. To conduct virtual training, previous work uses virtual reality (VR) to mimic the real world, without considering augmented reality (AR). Our goal is to simulate earthquakes in a familiar environment, for example in one's own office, helping users to take the simulation more seriously. With this approach, we make it possible to flexibly switch between different environments of different sizes, only requiring developers to adjust the furniture layout. We propose an AR earthquake simulation using a video see-through VR headset, then use real earthquake data and implement a novel AR screen shake technique, which simulates the forces applied to the user's head by shaking the entire view. We run a user study (n=25), where participants experienced an earthquake both in a VR scene and two AR scenes with and without the AR screen shake technique. Along with a questionnaire, we collected real-time heart rate and balance information from participants for analysis. Our results suggest that both AR scenes offer a more compelling experience compared to the VR scene, and the AR screen shake improved immediacy and was preferred by most participants. This showed us how virtual safety training can greatly benefit from an AR implementation, motivating us to further explore this approach for the case of earthquakes.

Keywords:

Augmented Reality, Virtual Reality, Real-time simulation, User study

*Master's Thesis, Graduate School of Science and Technology, Nara Institute of Science and Technology, July 31, 2021.

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1. Introduction

Many countries, especially counties and regions around the Pacific Rim, have to encounter earthquake disasters frequently. The damages from such incidents are tremendous and inevitable. For example in the last 10 years in Japan, there have been more than one hundred major earthquakes with recorded magnitudes greater than 5. For example, the 2011 Tohoku earthquake with 9.0-9.1 magnitude, caused catastrophic damage to the people and economy. The countries that suffer from earthquakes often have safety training programs for their population, especially at school. These programs are expected for the participant to prepare for a real earthquake incident and to reduce physical injuries of individuals [2]. Traditional earthquake safety training includes general information about the earthquake, emergency kit preparation, decision making during the earthquake, evacuation training, etc. After introducing all the information, participants are asked to hide under a table or other safe place to protect their head, pretending that an earthquake was happening. In this step, if the participant has not experienced a real earthquake yet, it is difficult to imagine how an earthquake at the place it question would really look like. This makes it difficult for them to be part of the situation and even harder to put the provided information to use during a real incident.

Prior work mostly focuses on using virtual reality (VR) to create a simulation experience for head-mounted displays (HMDs). The virtual environment is created using 3D models of furniture, which is arranged to mimic the real-world scenario. The scenario may vary depending on the setup, for example office, bedroom, kitchen, etc. This way, the situation can easily be manipulated to present users with information like guidance for how to use an emergency kit or how to evacuate properly. However, this pipeline offers a fully virtual environment, in other words, it brings users to another place they are unfamiliar with. The simulation results in a positive experience, but it is difficult for them to apply the knowledge they learnt in a real earthquake. To deal with this difficulty, we decided to use augmented reality (AR) to improve user experience of virtual earthquake safety trainings.

By using AR, users can experience what would happen if an earthquake occurred in their familiar environment. Although it is not possible to shake the real furniture, by shaking virtual furniture superimposed on the video background, they can feel the power of the earthquake and confirm the evacuation route. By using real offices and houses as the background, the user's sense of realism is expected to be greatly enhanced. However, one of the problems with AR earthquake simulation compared to VR is its limited ability of shaking of the entire environment. It is straightforward to shake the entire environment in VR, but in the case of video see-through AR, the camera is always fixed on the user's head and can only be moved through head movements.

To address this problem, we propose a novel rendering technique called AR screen shake. It emulates the motion of a physical camera by moving the entire rendered frame relative to the virtual camera. This allows us to create an AR earthquake simulation combining the advantages of VR—shaking the entire view—with the advantages of AR—providing a high level of realism in a familiar environment. To validate the effectiveness of the proposed approach, we conducted a user study that compared three conditions; VR earthquake simulation, AR earthquake simulation with and without the AR screen shake technique. The results suggest that participants prefer both AR conditions over the VR condition and that the condition with AR screen shake was the most preferred. The results also show that participants tend to lose their balance more in the AR condition with the AR screen shake.

The contributions of this paper are as follows:

- Demonstration of the successful AR earthquake simulation based on a consumer-grade HMD (Oculus Quest 2)
- Proposal of the AR screen shake technique to improve earthquake experience in video see-through AR
- Validation on the effectiveness of the proposed AR earthquake simulation and the AR screen shake technique

2. Related Work

2.1 Traditional Earthquake Safety Training

Those countries that have frequent earthquakes usually have their own way of conducting earthquake safety training. The training procedure varies depending on factors such as region, space, or cost. However, the purpose is always to reduce injuries of individuals during the earthquake. Most of the injuries during an earthquake are caused by falling objects (e.g. hanging picture or lamp), shattered objects (e.g. mirror or window), and heavy object falling over (e.g. shelf or wardrobe) [10, 11]. The common training procedure includes reading a safety manual [12, 13], watching a training video, and conducting an earthquake drill.

The safety manual includes topics such as preparation for the earthquake, organizing disaster supplies, objects to avoid to prevent injuries, etc. The training video shows a real earthquake scenario and the appropriate training process. The earthquake drill is the process training the participant on what to do during the earthquake and raise their preparedness, usually by applying the "drop, cover, and hold on" strategy [10, 11, 13]. **Drop** means to locate the nearest spot that is safe from falling objects and drop down to the floor to avoid being knocked down. **Cover** means to protect the head and other vulnerable parts of the body by covering them with arms or hands, and hide under a strong table or bed if available. **Hold on** means to stay at the safety spot until the earthquake stops. Conducting the training this way requires good imagination, which might be difficult for children or individuals without actual earthquake experience.

In our work, we focus on improving the impact of the safety training by taking the visualization to the next level. Combining the earthquake safety training with AR technology can increase the impact on participants' memory. With an immersive training experience, participants can take the training more seriously and will be able to memorize the lesson more clearly.

2.2 Virtual Reality Earthquake Safety Training

The increasing trend of using virtual reality leads to several VR earthquake safety training systems. Lindero Edutainment [1] takes full advantage of VR technology

Figure 1: The example scene of the game [1]. Left photo shows the safe spot after the earthquake end. Right photo shows the scene of the fire spreading through the house.

to create an earthquake safety training VR-based game on Steam. The game includes all major traditional safety training procedures, from providing basic knowledge, earthquake emergency kit preparation, to the earthquake scenario display. When starting the game, the player will begin in the ordinary western style house with a TV in front of them. The TV will present the earthquake prevention guide video to the player. Then, The player has to do the emergency kit preparation task by dragging all the specific objects required for the emergency kit to the box with the controller. After completing the preparation, the player will be guided to the safe spot which in this case is under the table, and the player is suggested to actually crawl on the ground. The scenario of the safe spot after shaking is shown in the left of Figure 1. The shaking motion of the earthquake in this game is the conventional shake in circular motion applied to the player's head. At the end of the earthquake scene, the fire will start and spread through the room as shown in the right of Figure 1 which the player is suggested to get out of the house immediately.

Li et al. [2] also use VR to develop an earthquake safety training using HTC Vive HMD. Their goal is to train the user to prevent the injury caused from the incident and raise the awareness to the incident of the user. The virtual environment that they used is designed to mimic various ordinary indoor scenarios. In case of Gong et al. [14], the designed virtual environment focus mainly on the

Figure 2: The left figure shows scene of one of the virtual environment used in the experiment [2]. The right figure show the same scene during the experiment with the avatar of the user.

dormitory scenario. The user will have the avatar in virtual space which is used to calculate the damage from the collision of the falling or tripping virtual furniture. The experiment is conducted in the open space where the user will have full mobility, thus the user can crouch and take cover to avoid the damage. This research confirm the effectiveness by re-experimenting in seven days and compare the summary damage. Figure 2 shows the example scene of the experiment. The result shows that VR training can significant reduce the damage from the earthquake to the user.

Feng et al. [3, 5, 15], Lovriglio et al. [4, 16], and Liang wt al. [17] used the VR technology to conduct the earthquake safety training which also focus on the evacuation training to improve the evacuee preparedness and decision making during the serious situation. Li et al. [18] designed the system on the different purpose which is to train the emergency rescue commander. The virtual environment is designed to mimic the real environment with Building Information Modelling (BIM)-based workflow which enable the high-level dynamic changes for the simulation. After that, they imported the building model in to Unity game engine to conduct the simulation. The user will experience the virtual earthquake through HMD which offer highly immersive experience. Feng et al. [3] and Lovriglio et al. [4] offer the haptic sensation to the user with the vibrating platform to increase

Figure 3: The shaking platform used the experiment of [3, 4]

the realism of the simulation experience as shown in Figure 3.

The user interfaces and voices are used to instruct the user to take the appropriate action during the serious situation and way-finding guidance user interface is used to guide the user during the evacuation training. In the case of Feng et al. [5], they have the interface to offer the user decision making task and real-time feed back. Figure 4 shows the example scene of the experiment. In result, their work proof that the VR training program give positive simulation experience to the user.

Suzuki et al. [6] take advantage of both VR and AI technology to design the AI-based earthquake safety training. The whole simulation are is reconstructed using multi-RGBD sensor system and SLAM framework to capture the room's geometry point cloud. The plane detection and object detection is performed on each texture applied to the point cloud. Then, the reconstructed room is projected in to the VR HMD and the earthquake simulation is conducted as shown in Figure 5.

However, a VR system brings users to another place they are unfamiliar with and it is difficult for them to apply the knowledge they learnt in a real earthquake. However, previous literature did not consider using AR to simulate the earthquake scenario. In our work, we focus on bringing AR closer to the safety training field, and we believe this can offer a more compelling experience to users. However,

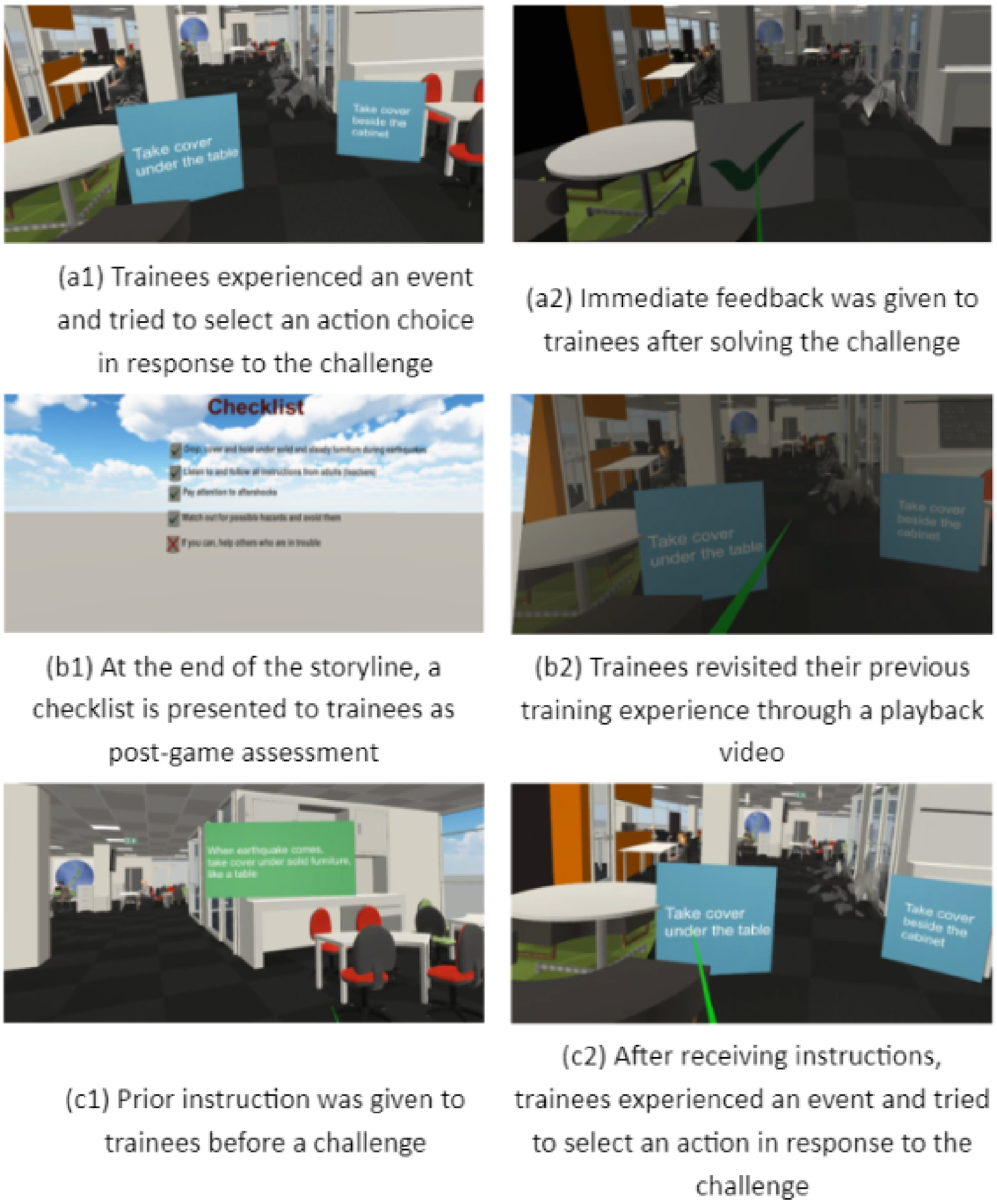


Figure 4: The example scene of the scene that the user have to experience during the experiment of [5].

Figure 5: The example scene of the earthquake simulation conducted by [6]

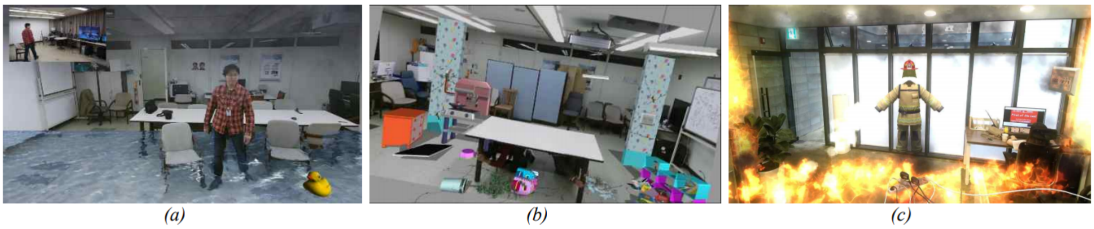


Figure 6: The example scene of various disaster scenario of [7].

a VR system brings users to another place they are unfamiliar with and it is difficult for them to apply the knowledge they learnt in a real earthquake.

2.3 Augmented Reality Simulation

Recently, there are many fields that use Augmented Reality technology for enhancing the visualization quality including the disaster prevention field. Jung et al. [7] take full advantage of the AR technology to visualize the scenario of fire, earthquake, and flood disaster for training the user to prevent the dangerous situation as shown in Figure 6. The interactive Spatial AR system along with Kinect SDK v.2.0 is used to conduct the earthquake safety training with the space and object recognition and human gesture recognition.

Catal et al. [8] introduce the AR game-based evacuation training which offer the realistic scenarios of the disasters (fire, chemical attack, and earthquake event) as shown in Figure 7. They use the mobile application using ARKit framework for training the user in the flexible training environment. Yamashita et al. [9] also use the AR for earthquake learning support through mobile devices. The experimental room have 4m * 4m area and have AR markers for the camera of an Android terminal to capture and spawn the 3D CG models as shown in 8.

Figure 7: The example scenes in various situation of the evacuation game [8].

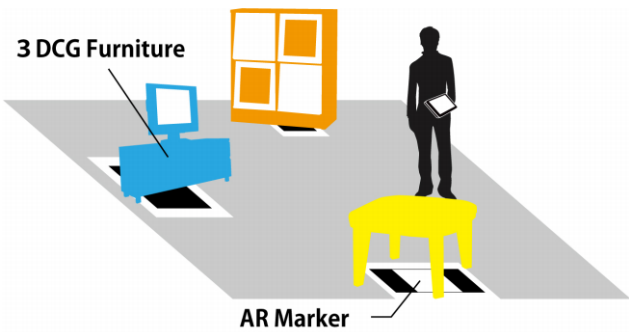


Figure 8: The experiment scene of [9] with the AR marker.

Lovreglio et al. [19–22] focus more on improving the evacuation task using AR technology and also provide a broad review on implementation of current AR-related disaster trainings. On the other hand, Mitsuhara et al. [23] use the AR for designing the training program for disaster prevention trainers to instruct the trainee properly with voice-based interaction. Wang et al. [24] already proved the effectiveness of AR for these types of simulations.

There exist two types of AR headsets; optical see-through and video see-through [25]. The video see-through approach offers higher flexibility in image processing while the optical see-through headset is generally more comfortable to wear. Moro et al. [26] used the optical see-through approach to create an AR simulation experience with the Hololens headset and Pfeil et al. [27] used the video see-through approach with an HTC Vive HMD and ZED Mini camera attachment.

However, none of the existing AR earthquake simulation systems addressed the problem of the inflexibility in the camera position. In this work, we create an AR-based earthquake simulation by using the video see-through approach with an Oculus Quest 2 headset and a ZED Mini camera attachment. The summary of the related work is listed in table 1.

Table 1: Related work summary

Related works	App	Device	Force applied to head	Imminent environment
[1], [2], [17], [6], [15], [3], [5], [16], [4], [18], [14]	VR	HMD	Yes	No
[7], [23], [27]	AR	Video see through HMD	No	Yes
[26], [23], [19]	AR	Optical see through HMD	No	Yes
[8], [9], [26], [23], [19]	AR	Mobile device	No	Yes
Our work	AR	Video see through HMD	Yes	Yes

3. Proposed Method

In the real earthquake incident, the earthquake force is applied to both people and environmental objects. Hence, the people feel the force applied to their body and are visually stimulated by the shaken environmental object. To simulate the earthquake incident, only the shaken environmental object does not offer enough realism to convince the user that their surrounding is shaken by the earthquake. The VR earthquake simulation takes this problem into account and adds the screen shaking effect in addition to the shaken environment to enhance the simulation experience. On the other hand, for AR earthquake simulation have the advantage in term of the realism of the imminent environment which is more convincing compared VR virtual environment. However, it's We consider the advantage of both VR and AR cases and come up with the method to take the advantage of both VR and AR earthquake simulation and improve the user's simulation experience even further.

We propose the technique called "AR Screen Shake" which is used to simulate the user's view during the earthquake incident by taking the force applied to their head into consideration. there are many ways to manipulate the user's view in VR such as a simple screen shaking effect which can be easily manipulated with the modern game engine. However, achieving the same effect in AR is quite challenging. A naive approach would be to shake the actual camera physically, but it would be very difficult to develop such a wearable force feedback device. We solve this problem by taking a two-pass rendering approach. In the first pass, we render virtual furniture onto the video background similarly to standard video see-through AR and store the rendered image as a texture buffer. In the second pass, we render a rectangle object (canvas) with the stored texture at an appropriate relative distance and orientation from the virtual camera. This is done twice per frame to keep stereo vision intact. It can be easily implemented in a modern game engine, for example using the RenderTexture feature in Unity. After having the canvas with the video background texture placing in front of the virtual camera, we can manipulate the movement of the canvas to simulate the shaking motion of the force applied to the user's head.

By doing the two-pass rendering, there are some differences in view between the first and the second pass. We set up the scene as shown in Figure 9 to

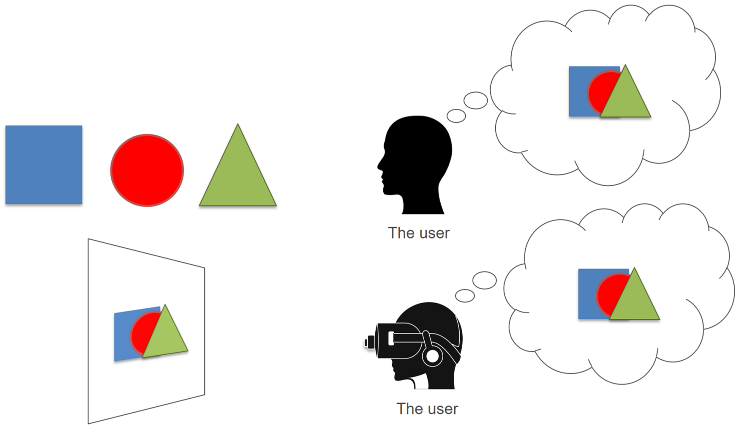


Figure 9: The comparison of view from the first and the second pass rendering result before moving the object and the canvas.

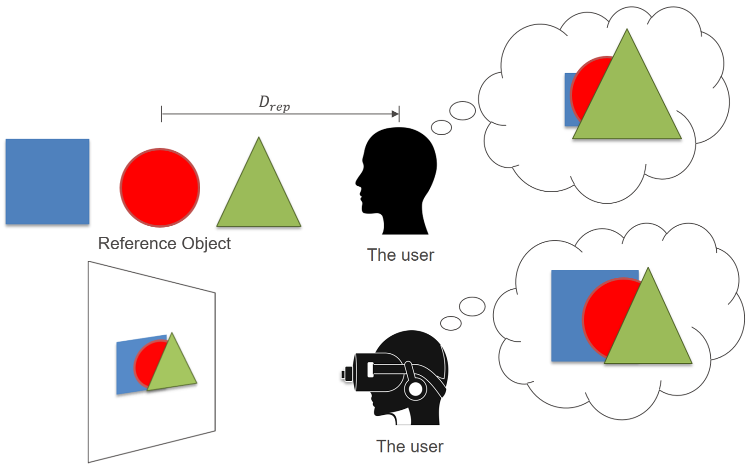


Figure 10: The comparison of view from the first and the second pass rendering result after moving the object and the canvas with the D_{rep} distance and reference object position.

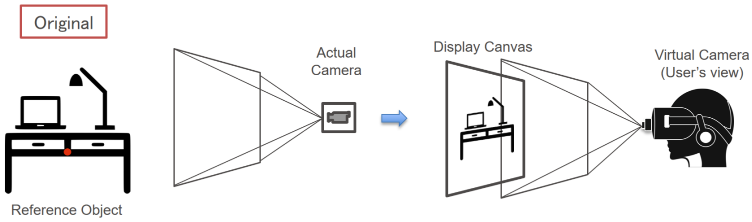


Figure 11: The setup of the “AR Screen Shake” system including the orientation of the reference object, the actual camera, the display canvas, and the virtual camera.

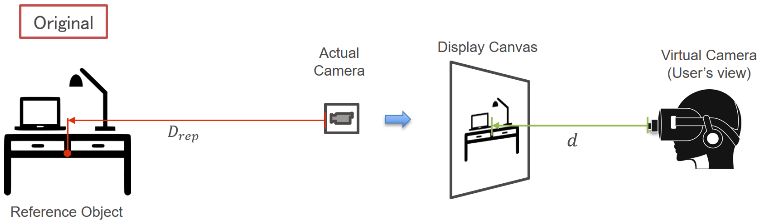


Figure 12: The setup of the “AR Screen Shake” with the distance D_{rep} and d.

show the visual effect that happens in our system. There are three objects set at different distances from the person in the top image. In the bottom image, a canvas displaying the scenario that the person would see before the object moves are placed in front of the person in virtual space. The view that the person would see in both conditions is the same. However, if we move all three objects and the canvas toward the person as shown in Figure 10, provided that the image on the canvas does not update, the view would not be the same in both conditions. The object that is closer to the user (the triangle) will get a lot bigger compared to the object that is further away from the person (the rectangle) which does not change the size much. This happens because the depth perception of the eye will be more accurate in moving 3-dimensional scene more the 2-dimensional scene. However, there is one specific distance that the object in both conditions will be rendered the object in the same size which in this case is the sphere. We call that distance as distance representative or D_{rep} as shown in Figure 10 and we call the object that is placed at the D_{rep} as “reference object”.

Figure 11 shows the setup of the “AR Screen Shake” system. The setup is divided into two-part, the left part is the first-pass rendering and the right part is

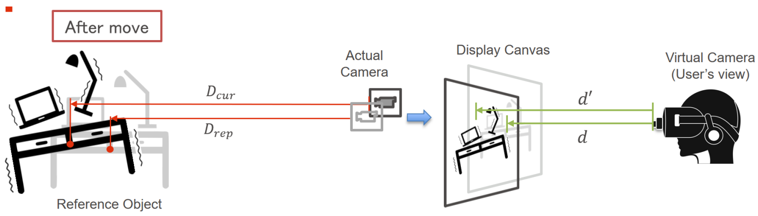


Figure 13: The setup of the "AR Screen Shake" after the earthquake starts with the distance D_{cur} and d'.

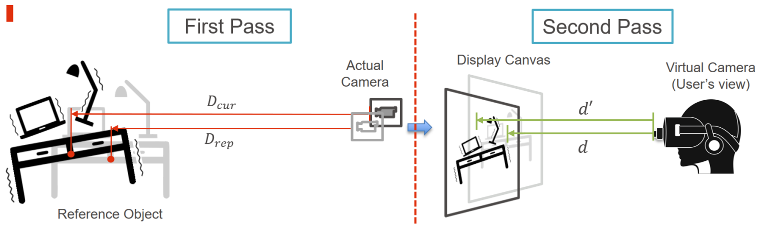


Figure 14: The setup of the "AR Screen Shake" separating the first and the second-pass rendering.

the second-pass rendering as shown in Figure 14. We used the ZED Mini camera as the actual camera for doing the video pass-through application which is placed in the virtual environment along with the virtual furniture. The actual camera will capture the view of the virtual furniture, including the reference object, and display the image on the canvas which is placed in front of the virtual camera using the RenderTexture. The virtual camera will capture the scene of the canvas with the image texture and display it to the user. As we described before, the distance from the actual camera to the reference object is D_{rep} and we define the distance from the virtual camera to the canvas as d as shown in Figure 12. After the earthquake simulation start, the virtual furniture and the actual camera will be shaken by the earthquake force. The shaking motion of the virtual furniture is captured and displayed on the canvas and the actual camera motion is simulated by moving the canvas object along with the actual camera motion. We define the current distance from the actual camera to the reference object as D_{cur} and define the current distance from the virtual camera to the canvas as d' as shown in Figure 13.

Even though the value of D_{cur} can be defined real-time in Unity, but the value of d' can not be directly defined. Since the scale between the first and the second-pass is different. In the first pass, the distances are defined in the room-scale but in the second pass, the distances are defined within the HMD scale. although, the scale between the first and second-pass is different, the proportion between them must be the same. Hence, we need to calculate the value of d' using the simple linear equation as shown in the equation 1.

$$\frac{d'}{d} = \frac{D_{cur}}{D_{rep}} \tag{1}$$

After solving the equation 1, we acquire the equation 2 which can calculate the value of d'. Then, the d' will be used to define the new position for the canvas to move to in each frame which is applied through the Unity scripting.

$$d' = \frac{D_{cur}}{D_{rep}} d \tag{2}$$

One apparent limitation of this technique is that the rendered scene in the second pass is just a rough approximation of what would be seen with physical camera motion. With consistent perspective, a 3D object will appear twice as big if the viewing distance is halved, while at the same to closer and farther objects will appear relatively larger or smaller. However, with the 2D canvas, all objects will change their apparent sizes uniformly regardless of their original spatial relationship. In other words, rendering will be correct only for a specific distance (D_{rep}). We can think of a few different strategies to address this issue. For example, D_{rep} can be the distance from the user to an important nearby object or to an object gazed on. Further investigation is necessary to optimize D_{rep} for the best user experience.

We compared the ideal views (full perspective rendering) and the corresponding views produced by our technique using a simple virtual environment. Figure 15 shows the configuration of the example scene to demonstrate the effects of our AR screen shake technique.

The scene contains two unique objects (with some distance between them) which were captured at varying offsets by the actual and virtual camera. The actual camera represent the ZED Mini camera in the real simulation which will capture original view or ideal view without distortion.

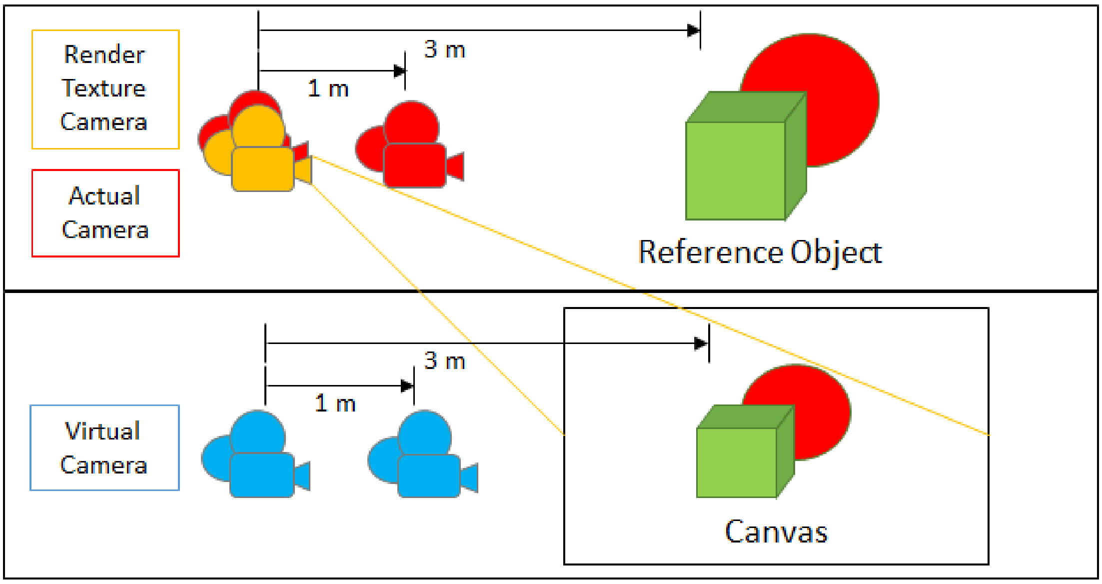


Figure 15: Configurations for the example views. A green cube (reference object) is 3 meters away from the actual camera. A sphere is behind the green cube. The two objects are rendered by the actual camera in the first rendering pass, displayed on the canvas, and then again rendered by the virtual camera in the second pass. We compare the views of the actual and virtual camera by moving both of them forward 1 meter.

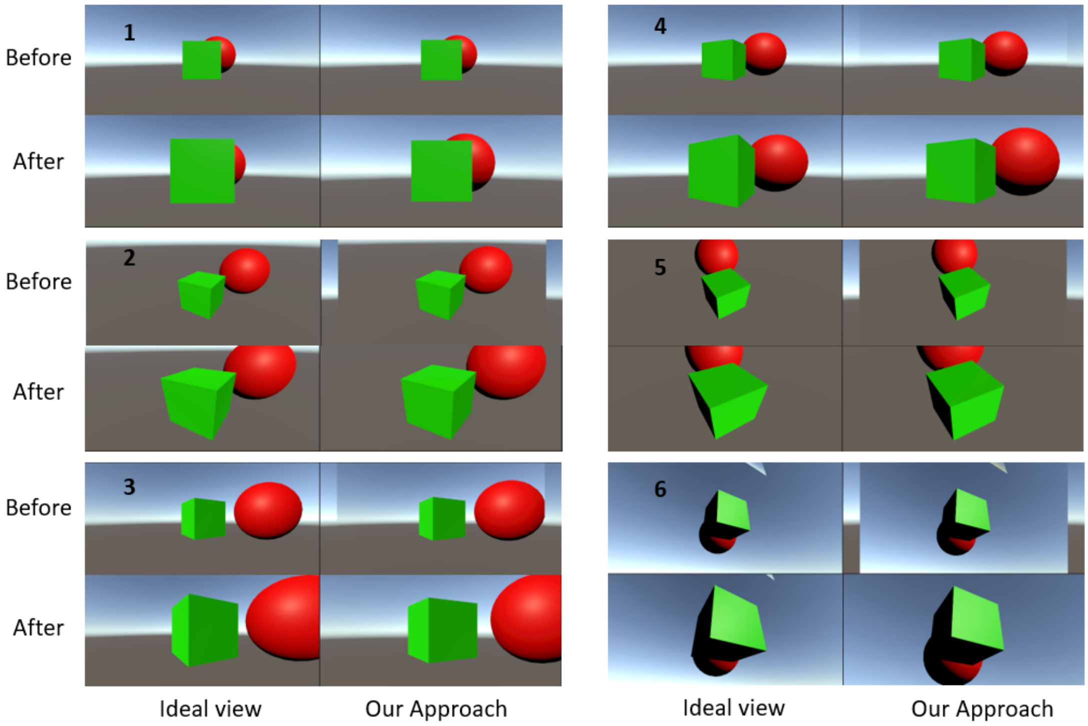


Figure 16: Example views from the simulated actual camera and the virtual camera in our technique from 6 example perspectives. We can confirm that our technique generally yields good approximation.

Figure 16 shows six example perspectives comparing the simulated actual camera and the virtual camera in our technique. There are slight differences between our approach and the ideal view in perspectives 2, 3, 4, and 5 which yield good results. However, in perspectives 1 and 6, there is a big difference between both conditions. This is because the overlap of the sphere and the rectangle in perspectives 1 and 6 is higher than the other perspective. When there are many virtual objects overlapping with each other in a single perspective, our approach could not yield a good rendering result. Despite that, in the video pass-through AR application which uses the HMD as the display, this problem does not obviously appear, since the user can easily change their perspective by turning their head. Hence, We can confirm that our technique generally yields a good approximation.

4. Implementation

Our simulation was built using Unity 2019.4.13 (ZED SDK 3.1) and was evaluated running on a system with 16 GB of RAM and an NVIDIA GTX 980 TI graphics card. Participants experienced the simulation through an Oculus Quest 2 HMD with a ZED Mini attached. Please see the supplementary video for our setup and the three conditions compared.

4.1 Mesh Reconstruction

Since physics interaction between real and virtual objects in earthquake simulation is essential, we acquire a 3D mesh of the real environment using the the ZEDfu application as shown in Figure 17. Prior works reveal the the effectiveness of this feature based on the common environment [28–30]. Reconstructing the whole simulation area will create the the mesh with a huge number of polygons which will soon be added to the Unity as convex mesh collider. However, the Unity program have limited the number of the polygons at 256 for a single game object. Thus, we use the spatial mapping feature of the ZED SDK which can enable while in the play mode in Unity. This spatial mapping feature solved the limited polygons of the Unity by creating many small meshes of the scanned area and parented them with the empty game object to make a big reconstructed mesh. After that, we parented the reconstructed mesh with the virtual floor which will be described in further section to have same movement pattern.

4.2 Building Structure Simulation

We created a simple building structure and added it to the virtual environment. The structure contains three main parts; floor, ceiling, and four poles. First, the floor was designed to be the simulation area where we put the real-world mesh collider and the 3D models. Second, the ceiling component which has kinematic property is added to be the pivot for preventing the floor to move out of the limited area. Finally, the poles are used to connect between the ceiling and the floor. With this process, we obtain the building structure that has physics property for the indoor scenario. A double configurable joint is added to the top

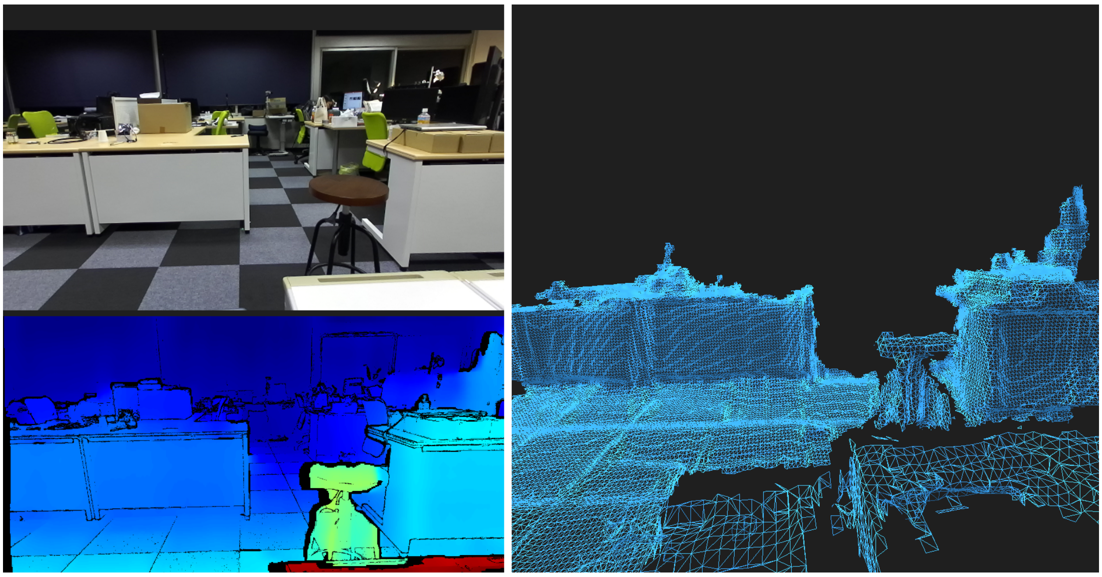


Figure 17: ZEDfu application interface while capturing the depth information around the room

and bottom of each pole with the limited degree of movement. Finally, a drag function is added to the poles and the floor to simulate the friction between the components.

4.3 3D Model

After having the intractable real-world mesh and building structure, we then add some 3D models to make the scene look realistic. We use public complete 3D model, then add those models to empty spaces in the real-world mesh collider. Next, to add physics properties to the 3D models and real-world mesh, we add a Rigidbody component to them. For the mass of each object, we set the approximate mass of each object according to three object categories; 1 for small objects such as a book and a cup, 3 for medium size objects such as a chair, and 5 for large objects such as a table and a shelf. Following the force equation, these mass values will then be multiplied by the acceleration force added to the floor. To achieve the maximum realism of the earthquake, we do not modify the acceleration data from the real earthquake, so we set the mass of the floor to 1. After that, we register the 3D models onto the video background.

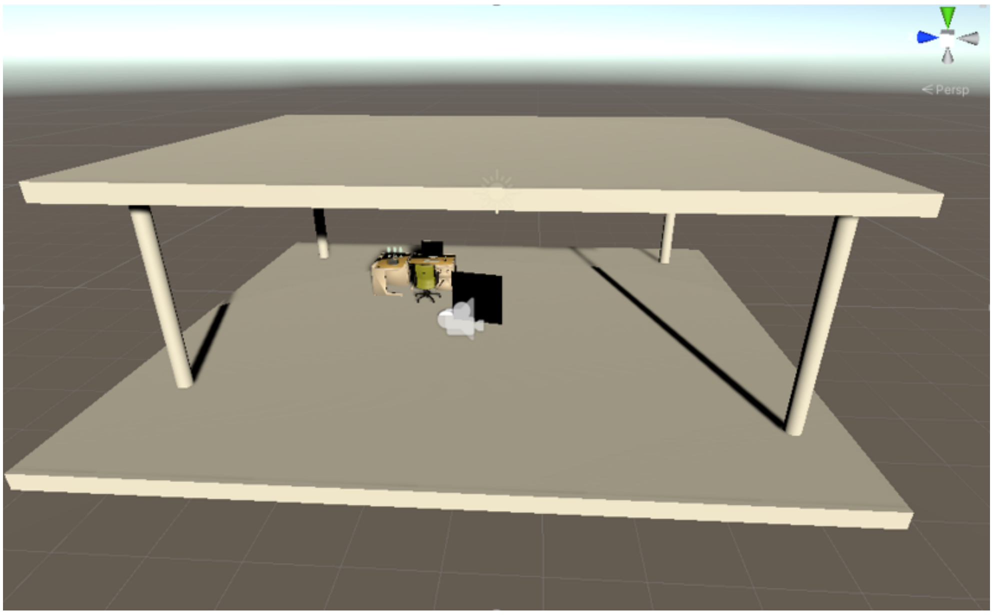


Figure 18: The platform used for simulation

4.4 Earthquake Simulation

To achieve realistic shaking, we use recorded acceleration data from real earthquakes. The data is derived from a seismic graph and provides acceleration values for three axes: North-South (NS), East-West (EW), and Up-Down (UD) indicating the direction of the acceleration as shown in Figure 2. The dataset used in our study has been recorded and made publicly available by the Japan Meteorological Agency [31]. For a realistic simulation, the acceleration data is directly applied to the virtual room using the "RigidBody.AddForce" function of Unity's physics engine. The virtual floor already contains a (previously generated) real-world collider, which shakes loose 3D models realistically.

4.5 AR Screen Shake

As discussed in Sec. 3, D_{rep} should be carefully selected to best approximate the user's view, because it is the only distance rendering will be correct at. In our implementation, D_{rep} is simply fixed to 3 meters as it is the distance from the participants to the wall where most 3D models of virtual furniture are overlaid.

Table 2: The example of the acceleration data that we used for the simulation.

Site code 38.1033 142.86		
LAT. = 38.5401		
LON. = 141.1272		
Sampling rate = 100Hz		
Unit = gal(cm/s/s)		
Initial time = 2011 03 11 14 46 30		
NS	EW	UD
-0.004	-0.001	-0.01
-0.038	0.023	-0.018
-0.006	0.016	-0.02
0.025	0.007	-0.015
0.004	-0.007	-0.011
0.016	0.007	-0.01
-0.002	0.012	-0.015
-0.004	-0.02	-0.013
0.005	-0.044	-0.007
-0.007	-0.011	-0.001
0.006	0.024	0.003
0.015	0.01	0.001
0.016	0.009	0.001
0.016	0.009	0.001
0.014	-0.012	0.001
0.013	-0.01	-0.006
0.003	0.007	-0.011
-0.001	-0.026	-0.002

5. Experiment

We designed the experiment based on the following four hypotheses.

H1 Presence and believability of the earthquake are higher in AR when compared to VR.

H2 Presence and believability of the earthquake are higher with our AR screen shake technique than without it in AR.

H3 Postural instability is higher with our AR screen shake technique than without it in AR.

H4 Heart rate is higher with our AR screen shake technique than without it in AR.

5.1 Participants

We recruited 25 participants in total to take part in the experiment, aging from 20 to 30. All of them are from our graduate school, from varying fields of study. The participants' background about VR and AR familiarity and earthquake experience is also varied.

5.2 Procedure

The first step is to explain the procedure of the experiment and basic knowledge about the earthquake safety training. The participant has to fill in the pre-questionnaire before starting the experiment to measure how familiar they are with the virtual environment and earthquakes. Then, we ask them to watch a video clip of a real earthquake incident and memorize the scenario which will be compared with the simulation scene. After the preparation is done, we tell the participant to wear the Polar heart rate sensor, help them to adjust the HMD strap, and have them stand on the Wii Balance Board as shown in Figure 19. Then, we tell the participant to rotate just their head, not the whole upper body to avoid unnecessary noise in balance data.

Figure 19: The participant wearing the Oculus Quest 2, Polar heart rate sensor, and Wii balance board during the experiment.

The participant has to experience three conditions for the experiment and will be asked to answer a questionnaire after each condition. The first is a VR condition which is considered the baseline to be compared with the AR conditions. The second is a normal AR condition without the AR screen shake (ARNS). The third is an AR condition with AR screen shake (ARS). Participants always start with the VR condition, but the order of the two AR conditions is alternated to avoid bias on seeing one scene before the other. A half of the participants start with ARNS, then ARS, and the other half start with ARS, then ARNS. To avoid bias, the two AR conditions are conducted in different rooms with slightly different earthquake data. Thus, participants have to walk between the two rooms, which approximately took five minutes including equipment setup. The average length of each condition was around 1 minute. The example scenes of each conditions is shown in Figure 20, 21, 22.

5.3 Evaluation

In this experiment, we collected three types of data: heart rate, center point of pressure (COP, used for balance analysis), and questionnaires.

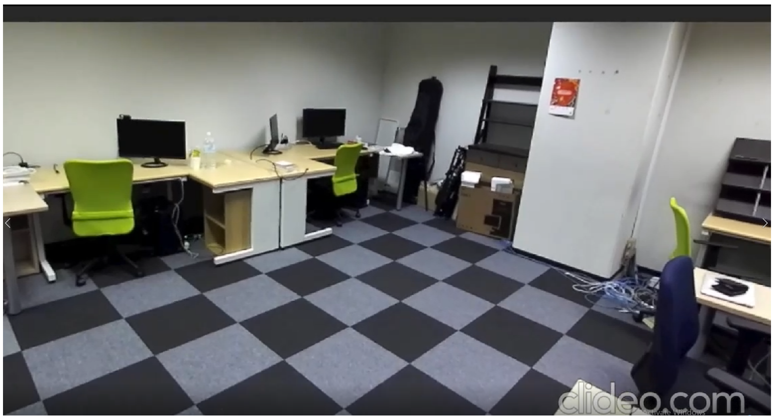
Since in a real earthquake situation people usually feel panic or fear, we measured participants' heart rate using the Polar Verity Sense. The device was connected to the Polar Sensor Logger app via Bluetooth, which then recorded the transmitted measurements at a rate of 1 Hz. The sensor itself was attached to the participant's arm for the entire duration of the experiment. The relevant sections were then extracted from the recording by synchronizing it with the timings recorded by the Unity application.

According to our **H3**, we believe that the **AR screen shake** technique will cause participants to lose their balance more during the simulated earthquakes. Therefore, we recorded balance data using the Wii Balance Board (WBB). In the intended use case, users will be able to walk freely within the play area of the Oculus Quest 2. However, for this experiment, we asked participants to stand reasonably still on the WBB, making it possible to measure effects on their balance. The WBB was connected to a modified version of the Windows Forms application "Wii Balance Walker [32]" via Bluetooth, which recorded COP measurements at a rate of 16 Hz. The resulting data was then merged with the

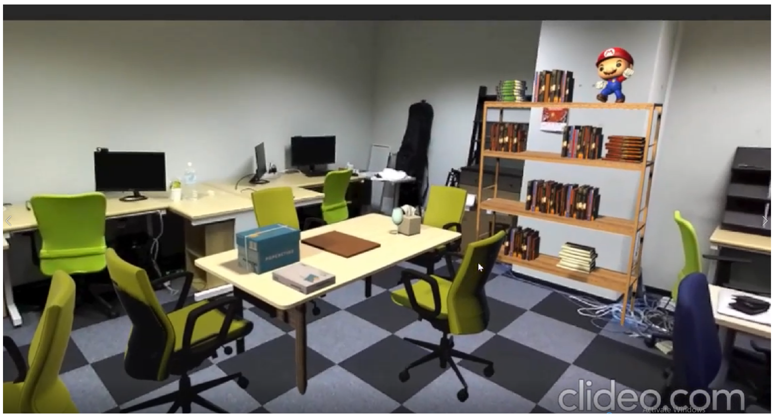
(a) The virtual reality scene before the earthquake start

(b) The virtual reality scene after the earthquake start.

Figure 20: The example scenes of the experiment in VR scene.



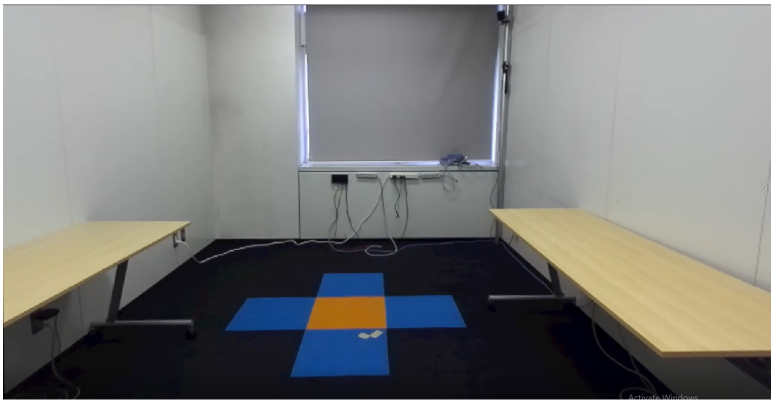
(a) The simulation area without the virtual furniture.



(b) The simulation area with the virtual furniture.

(c) The simulation are during earthquake.

Figure 21: The example scenes of the experiment in location 1.



(a) The simulation area without the virtual furniture.

(b) The simulation area with the virtual furniture.

(c) The simulation are during earthquake.

Figure 22: The example scenes of the experiment in location 2.

heart rate data in the post-processing phase using R's data.table class with the parameter roll = TRUE. Before this step, we shifted the times recorded by devices other than the main PC by the (afterwards determined) difference in system time.

To evaluate simulation experience, we use a custom questionnaire created using Google Forms. Due to the fact that there are more than one condition that the participant needs to experience in each experiment, we designed the questionnaire to record the participant experience after finishing each condition to prevent them from forgetting the feeling when experiencing multiple conditions. There are three questionnaires in total that the participant needs to fill out in each experiment, which are pre-questionnaire, main questionnaire, and post-questionnaire. Before starting the experiment, the participants have to fill out the pre-questionnaire. This questionnaire is designed to gather the participants' general information and their familiarity with earthquakes and VR/AR technology.

Table 3: Post-questionnaire items in the experiment.

item	question
a	Do you have any earthquake experience?
b	If yes, what was the earthquake magnitude that you felt at that time?
c	Have you ever done earthquake safety training?
d	How familiar are you with VR/AR?
e	How much knowledge about earthquakes do you have? - You can imagine how your place will look like in the earthquake incident - You know how to evade the damage in earthquake incident that could happen to you - You know how to take care people around you in the incident - You know where are the safe spot in your own room in earthquake incident - You know the earthquake emergency kit
f	What kind of knowledge do you want to get about earthquakes? - What will it look like if the earthquake is happening in current spot - Response act in the earthquake incident - Evacuation training - Earthquake emergency kit - Cause of the earthquake - It's going to be fun

Table 4: Main questionnaire items in the experiment.

item	question
a	The realism
b	The feeling part with the situation
c	The dynamics of the scene
d	The earthquake looks real
e	Overall simulation score (ref video)
f	Overall simulation score (traditional way)
g	The earthquake is coming soon
h	The earthquake is happening
i	The furniture movement looks real
j	Feeling dizzy
k	Feeling scared/panic
l	Feeling swung by earthquake force

After that, the participant is asked to fill out the main questionnaire after experiencing the each of the VR, ARNS, and ARS conditions. These questionnaires are designed to evaluate the participant experience on the most recent condition which include 12 features listed in Table 4.

From Table 4, the question (a)-(e) are evaluated based on the comparison with the reference video that we show to the participant before starting the experiment on a scale of 1-5 where 1 is "worst" and 5 is "best." Questions (f) and (g) asked the participant to give an overall rating of our system compared to the reference video and the traditional earthquake safety training. Questions (h)-(l) are evaluated based on the participant's feelings on a scale of 1-5 where 1 is "worst" and 5 is "best." The data in Table 4 will be used to evaluate the effectiveness of our proposed method.

The post-questionnaire was designed to evaluate the overall experience of the participant after experiencing all the conditions. This section is the final evaluation of our system which allows the participant to select their preferred condition based on the same category as the previous questionnaires. It also evaluates effectiveness in terms of improving the participant's interest in earthquakes. The content of the questionnaire is shown in Table 5.

Table 5: Post-questionnaire items in the experiment.

item	question
a	Select your preferred condition based on these categories - The realism - Feeling part with the situation - The dynamics of the scene - The earthquake looks real - The dizziness - Personal preference
b	This experiment make you feel interested in earthquake incident

Question (a) from Table 5 asked the participant to choose a condition from the experiment (VR, ARNS, and ARS) that best represents the listed category. This question is the post experiment evaluation from the participant that can indicate the overall effectiveness of the system and our proposed method. The data from question (b) and (c) will be used to evaluate increased interest in earthquakes and preparedness.

6. Results

As described in the previous section, we gathered three types of data during the experiment: questionnaires, balance (COP), and heart rate.

6.1 Questionnaires

We perform Aligned Ranks Transformation ANOVA analysis first to find significant differences between groups. Figure 23 shows the result of questionnaire analysis.

From Fig. 23, each sub-graph represents the summary of the answer from each item in Table 4. The result from Aligned Ranks Transformation ANOVA analysis shows that out of 12 question items, 8 yielded a statistically significant difference (SSD). These are (a), (c), (d), (e), (f), (j), and (k). Wilcoxon Signed Rank Tests were used to perform pairwise tests between the conditions VR and ARNS, VR and ARS, and ARNS and ARS. We adjusted the p-value of items with SSD using the Benjamini & Hochberg method (BH) [33].

Figure 23(a) shows the realism score when compared with reference video in three conditions VR, ARNS, ARS. From ANOVA, we found an SSD (F(2,48) = 13.405, $p < 0.001$) and the BH method found SSDs between VR and ARS ($p < 0.001$) and between ARNS and ARS ($p < 0.01$). Figure 23(c) shows the dynamics of the whole scene comparing with reference video for all three conditions. The ANOVA analysis found an SSD (F(2,48) = 7.7716, $p < 0.01$) and the BH method found SSDs between VR and ARS ($p < 0.05$) and between ARNS and ARS ($p < 0.05$).

Figure 23(d) shows how much the simulation can convince the participant that the earthquake is real for all conditions. An ANOVA found an SSD (F(2,48) = 12.741, $p < 0.001$), and the BH method found SSDs between VR and ARNS ($p < 0.05$) and between VR and ARS ($p < 0.001$). Figure 23(e) represents the overall score of all three conditions comparing with the reference video. An ANOVA found an SSD (F(2,48) = 13.447, $p < 0.001$) and the BH method found SSDs between VR and ARS ($p < 0.001$) and between ARNS and ARS ($p < 0.001$).

Figure 23(f) represents the overall score of all three conditions comparing with the traditional training. An ANOVA found an SSD (F(2,48) = 6.1606, $p < 0.01$)

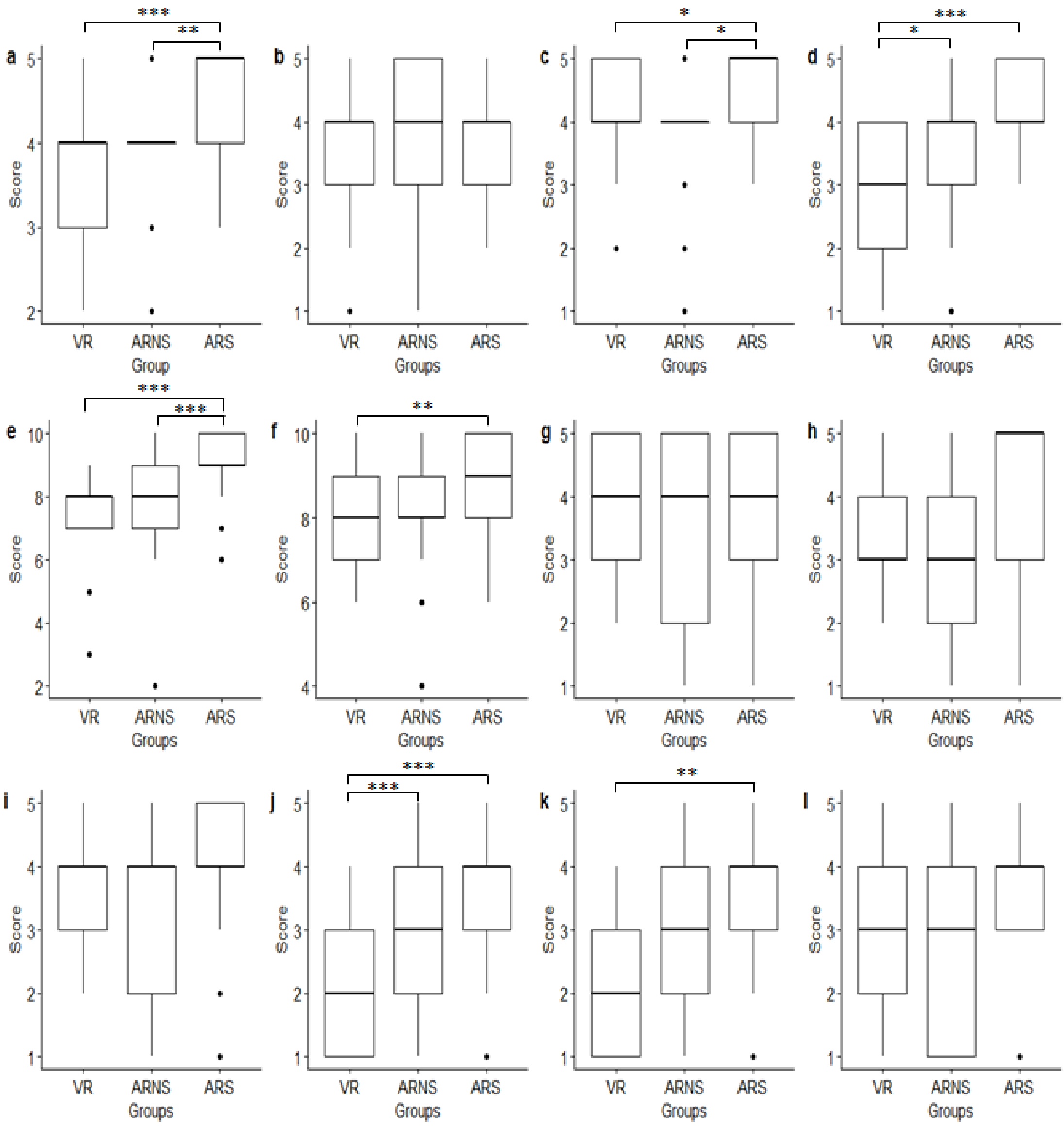


Figure 23: A visual summary of all questionnaire answers with significance annotated by stars per category (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

and the BH method found SSDs between VR and ARS ($p < 0.01$). Figure 23(h) shows the feeling of experiencing earthquake during the experiment. An ANOVA found an SSD (F(2,48) = 5.1711, $p < 0.05$), however, the BH method did not find a SSD between any condition pair after the p-value adjustment.

Figure 23(j) shows the dizziness of the participant during the experiment. An ANOVA found an SSD (F(2,48) = 14.71, $p < 0.001$) and the BH method found SSDs between VR and ARNS ($p < 0.001$) and between VR and ARS ($p < 0.001$). Figure 23(k) shows the scared/panic feelings of the participant during the experiment. An ANOVA found an SSD (F(2,48) = 6.9187, $p < 0.01$) and the BH method found SSDs between VR and ARS ($p < 0.01$).

Lastly, the post-questionnaire asked the participant to select their preferred condition. In summary, the results from Table 5(a) show that participants prefer the AR condition with our AR screen shake technique applied over other conditions when it comes to visual realism (VR: 12.5%, ARNS: 29.17%, ARS: 58.33%), the dynamics of the scene (VR: 8.33%, ARNS: 20.83%, ARS: 70.83%), realism of the earthquake (VR: 4.17%, ARNS: 37.5%, ARS: 58.33%), and personal preferences (VR: 4.17%, ARNS: 33.33%, ARS: 62.5%). The result from Table 5(b) shows the increasing interest in the earthquake incident of the participant after the experiment which there are 12% of the participant very interested and would like to learn more about earthquake, 64% feel moderately interested, 24% feel a little interested, and 0% feel the same as before the experiment.

6.2 Balance

According to **H3**, we expected participants to feature more postural instability when experiencing AR screen shake. Oftentimes, balance is measured in terms of the total path length that the COP produced after a longer amount of time, but this way of measuring balance is more fit for situations in which the goal is to keep as still as possible. Figure 24 shows the comparison of the COP between the ARNS and ARS. Figure 25 shows our more qualitative approach to analyzing balance data. After calculating a density map of the (centered) COP point clusters of all participants and simplifying the density information, a clear difference between the ARNS and ARS conditions becomes visible.

Another important aspect of COP movement is how it evolved over time.

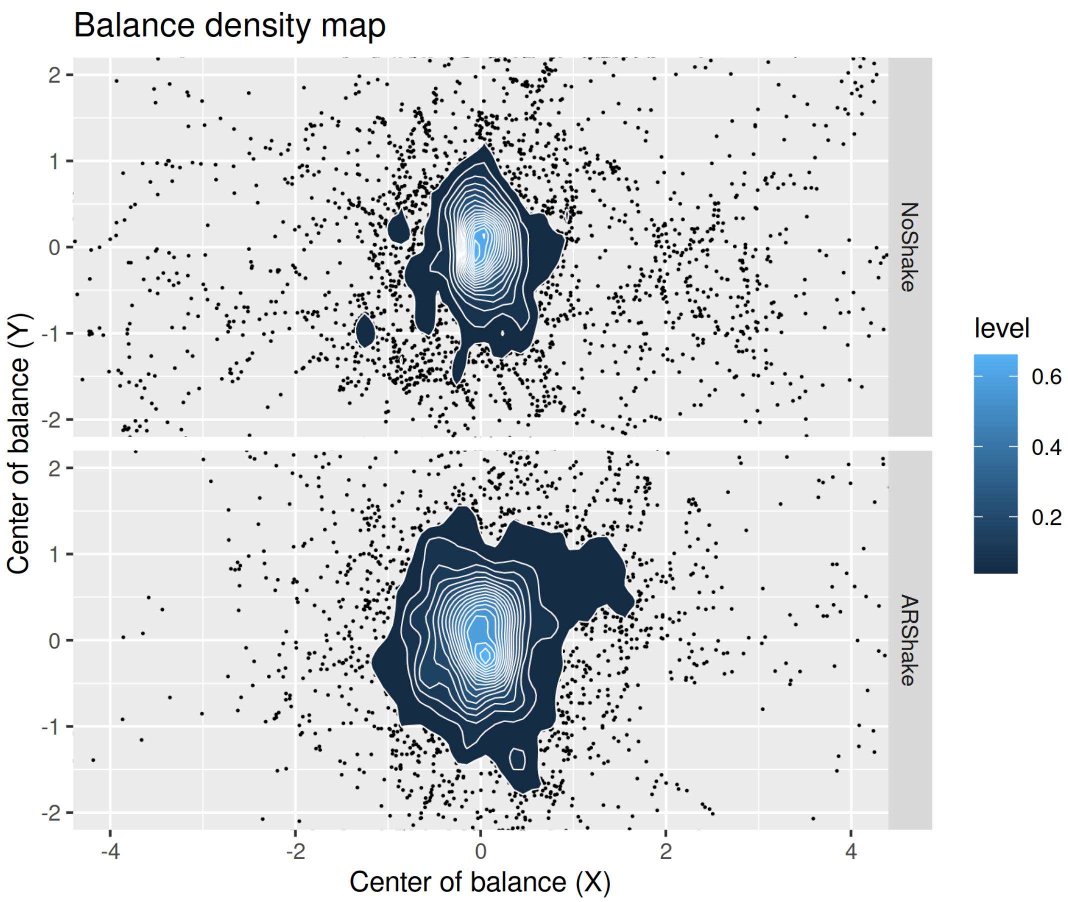


Figure 24: Density maps for the COP of all participants during earthquake movements, separated by shake condition. Units are in centimeters. Generated using R's **stat_density_2d()** with bins = 18.

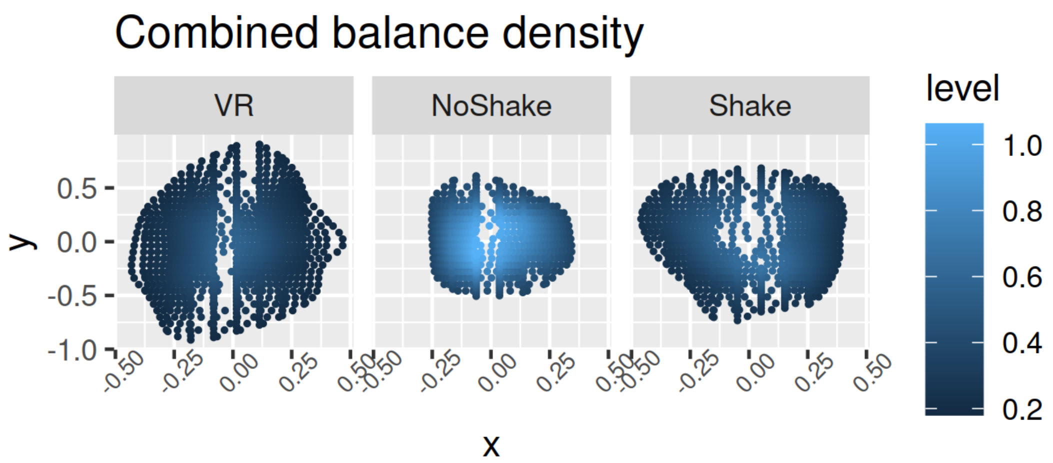


Figure 25: Comparison of simplified density maps for the COP of all participants during earthquake movements, separated by shake condition. Units are in centimeters. Generated by extracting level points from R's **stat_density_2d()** and filtering levels below level mean per group, yielding the "core" of each density map.

Figure 26 compares COP accelerations between screen shake conditions, separated by AR scene. This gives useful insights as to when participants shifted their balance the most. Since the acceleration patters from the two AR locations ended up being quite different, they are presented separately. Please refer to the supplemental video to see the differences between the two locations.

6.3 Heart Rate

We recorded heart rate to support **H4**, which says that the impact of the earthquake will generally cause participants to be more excited and therefore feature increased heart rate. Figure 27 shows smoothed heart rate curves for all participants for all scenes and screen shake conditions. We separate AR locations to overlay less data in the same facet and avoid overplotting. No general trend can be seen, a statistical comparison between "pre-peak" and "after-peak" heart rate means did not yield significant results.

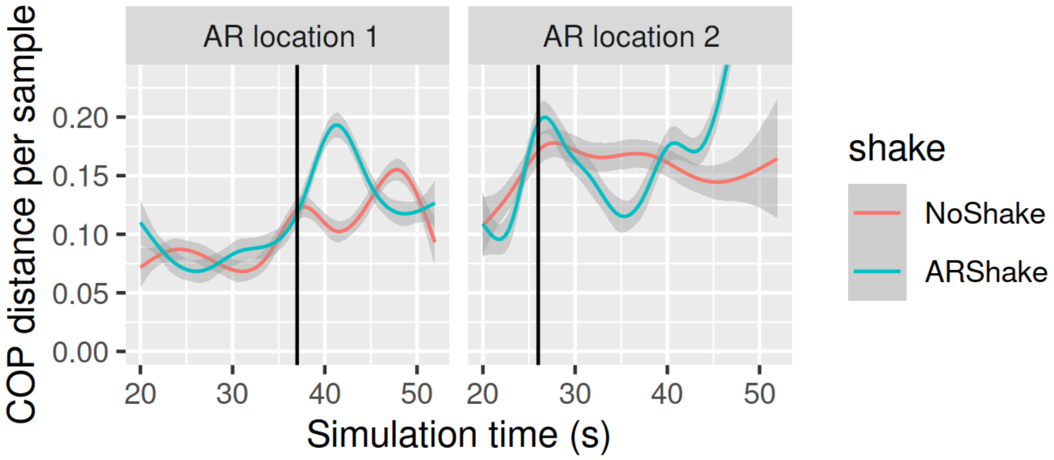


Figure 26: Comparison of smoothed acceleration per COP sample for all participants during earthquake movements, separated by AR scene and grouped by shake condition. The black line represents the earthquake's "peak" of intensity. Units are in centimeters.

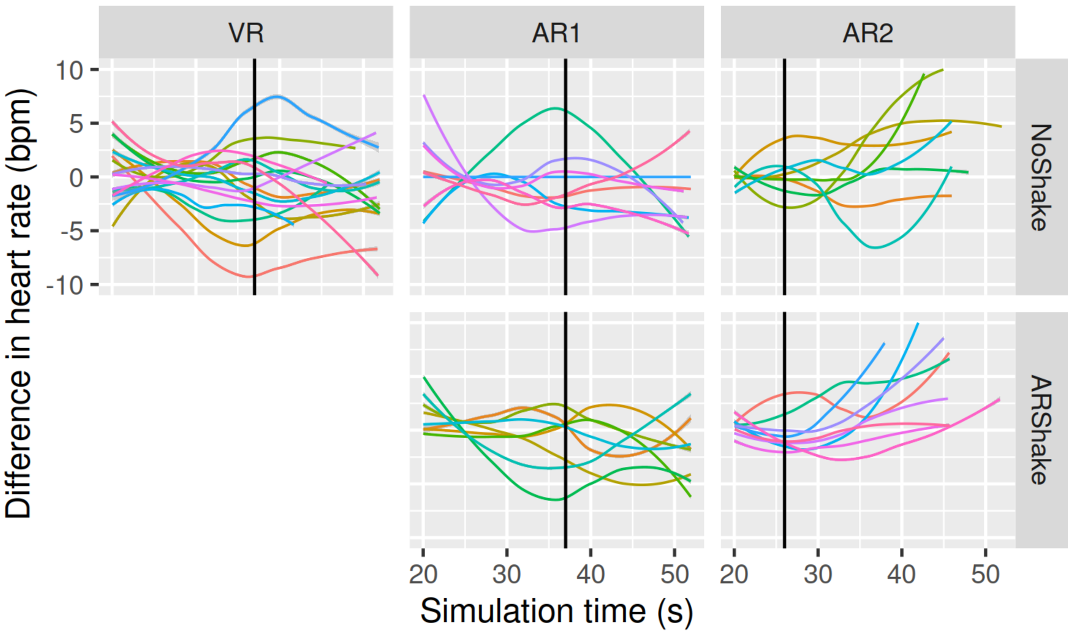


Figure 27: Smoothed difference in heart rate per participant, starting from the first earthquake movement, separated by scene and screen shake condition. Units are in heartbeats per minute.

7. Discussion

We used the score from the main questionnaire to evaluate presence and believability. Our results show significant differences when comparing VR to ARNS and ARS. VR presented a lower score, which completely supports our **H1**.

H2 was partially supported by our results. Figure 23(a), (c), and (e), show SSDs between ARNS and ARS (a; $p < 0.001$, c; $p < 0.05$, e; $p < 0.001$) and the score of ARS is higher than ARNS in these items.

We performed a statistical comparison of balance density core areas per participant without receiving significant results. We assume that ANOVA is not adequate for analyzing this type of data, at least not without weighting the area using the distribution of density level in it. There are many positive comments from the participant about the balance shifting during the experiment for example, "I almost felt like I was moving," "The movement was volatile, giving me the illusion that my body was shaking," etc. Our visual analysis of balance COP density cores also shows clear differences in Fig. 25. However, a quantitative analysis of the respective questionnaire item did not result in an SSD as shown in Fig. 23(l). We think this is because participants understood this question to concern real sensory input, not just a slight loss of balance. While some doubts might arise as to why VR features noticeably less COP density in Fig. 25, too, we think this can be explained by the Postural Instability Theory, which suggests that users are generally more prone to losing balance in VR [34].

That said, the smoothed accelerations over time shown in Fig. 26 clearly indicate a reaction in balance at the peak of the earthquake. Our explanation for why AR screen shake only has a clear effect for AR location 1 is that AR location 2 featured a much more intense earthquake. On top of this, the room was also smaller, shaking the furniture much stronger than in AR location 1. This interpretation was also supported by multiple participants, commenting that AR location 2 had a much more intense earthquake. In conclusion, we think that with the current means of analysis available to us, there is more evidence that **H3** is true than there is to show the opposite.

No qualitative or quantitative evidence was found to support our hypothesis regarding heart rate. Although there is a general rising trend for AR location 2 with AR screen shake, no other conditions show this effect. We think this might be because of (1) a weaker effect of the earthquake experience on heart rate than expected and (2) the fact that participants physically moved between conditions and then stood still during the earthquake, which might have resulted in a trend of generally decreasing heart rates in the observed time window. We further think that the combination of our AR screen shake technique *and* the more intense earthquake simulation at location 2 resulted in the most noticeable rise in heart rate. Since this analysis does not take into account heart rate variability, we plan to add this measure to future experiments. In summary, we reject **H4**.

8. Future work

8.1 Limitations

One limitation is that there was no reference video available for the real earthquake incident which we took the acceleration data from. The reference video we showed to participants is a general earthquake recording not actually related to the acceleration data. In this experiment, we used Unity's inbuilt physics engine to simulate virtual object movements based on the acceleration data. Therefore, we have not validated that our generated shaking motions are replicating exactly what happened during the original earthquake. Concerning this limitation, we focused more on optimizing the simulation experience rather than exactly recreating the earthquake incident. To achieve that, we asked several individuals who have experienced a big earthquake to optimize the realism.

Second, the condition order is not counter-balanced. As mentioned in the experiment procedure, participants always started with the VR condition, then ARNS and ARS in a randomized order. Because we don't have the VR condition counter-balanced, we focus more on the two AR conditions. We have a plan to recruit more participants for fully counter-balanced ordering, however, we had to terminate the experiment in the middle due to COVID-19.

Third, participants mentioned that in the AR conditions, some virtual objects sunk into the real floor or wall, which is due to the limited accuracy of the depth-sensing function of the ZED Mini camera. Obtaining accurate depth data of the surrounding environment is challenging, especially from a far distance or for plain-colored walls. In AR location 1, there are only a few comments on this issue compared to AR location 2. We suspect this is because AR location 2 is an empty room with plain-colored walls and more distance to the wall facing the user. Similar to "breaks in presence" in virtual reality [35], which break the illusion of being at a virtual place, we expect this to break object presence (the illusion that the virtual objects are real). As of now, we cannot say how much this affected the immediacy of the earthquake simulation felt by participants. We believe that in the future, depth-sensing technology will be enhanced further and this limitation will disappear.

Forth, limitation and the most frequent feedback from participants is the lack of haptic sensation. One of the biggest differences between the real earthquake situation and the earthquake simulation is that the participant can feel some force applied to their body during the real incident. In our work, we compensate for this limitation with the AR screen shake technique, but it seems that it takes more to completely convince users. There are many ways to improve this, but most of them require a complicated and expensive setup (such as a shaking chair) or collaboration with a disaster prevention museum to gain access to a shaking floor. However, implementing the simulation on that basis will contradict our main purpose, which is to create an AR earthquake simulation which can simulate earthquakes in a familiar environment, using consumer-grade equipment.

Lastly, it is necessary to have enough space in the real environment to place the virtual objects. If there is not sufficient space to put enough virtual objects, users will not be convinced because most parts of the scene are static. Most of the users will want to run the simulation at their home or office, which often does not offer enough space. One solution could be the use of high-accuracy image recognition to diminish reality and gain more space [36], but this would also lead to a less familiar environment. Ideally, our system would combine diminished reality and object recognition technologies to shake auto-segmented 3D models of the actual furniture in the real room.

8.2 Research agenda

To further develop the AR screen shake technique, we would like to investigate further on several topics. First, we would like to improve image distortion in the second rendering pass to make it more natural. As mentioned in Sec. 3, we encounter the distortion problem while there are many virtual furniture intersect together in the field of view which cause some unwanted effect on camera movement. To address this problem, we plan to improve the second pass rendering process further by applying a more complex algorithm to minimize the distortion.

We also plan to expand the system to full-fledged earthquake preparedness and response training. For the full training application, a convincing sound system and proper user interface to instruct the user is required which our research did not focus on both things. Hence, we plan to integrate a realistic sound system and a user interface to teach appropriate behaviors under an earthquake. The sound system that we used in this simulation is the open-source sound effect that is available to use. We select the sound effect manually to match the sound of the earthquake in our experimental area which is totally the approximation of the implementer. The sound system that we want to implement in the future is the real-time sound system that can react to events in real-time such as the table shaking sound, the chair clashing with the table sound, the broken glass sound, the floor cracking sound, etc. Having a convincing sound system can raise the user's presence and awareness of the changing environment around them. The user interface is one of the most important features in the training application that is used to present the information to the user. To implement our research to the full training application, we need a proper user interface to inform the important knowledge about earthquake and training to the user and instruct them the appropriate action in an earthquake situation. The training application will be designed according to the standard procedure of earthquake safety training which includes the explanation and action. In the explanation part, we can use the simple text interface that appears in front of the user instructing any information that the user needs to know. In the action part, we can use the highlight interface to represent the safe spot in the earthquake incident and the arrow representing the evacuation route, and so on. With the sound system and user interface system implemented, we believe that the application will offer a more compelling and easy-to-remember experience to the user.

The other problem that some of the participants from the experiment mentioned in the static environment. The participant mentioned that "The surrounding environment is not moving", "The desk in the surrounding is now moving compared to the center one", etc. Due to this issue, some of the participants tend to lose their focus on the event when they notice the mismatch movement between the virtual and real furniture. In the VR application, this problem can be solved easily because all the event is done in virtual space but in AR application, this problem is still a challenge. A way to address this problem is to use the Diminished Reality (DM). The DM is the technology that can diminish the real object in the real world and replace it with the prediction of the background texture behind the diminished object. Our ideal thought to apply this technique to our work is to diminish all the objects in the room and replace them with virtual furniture. If we can achieve that, we will have the full intractable mixed reality scene where the user can walk around and interact with all the objects virtually then suddenly the earthquake appears and all the objects in the room react according to the earthquake force. However, DM technology is still a developing technology and does not have enough capacity to seamlessly diminish all the furniture in the room at once. When the DM technology has enough capacity to do all the work, we expect to apply this technique to our work to improve the efficiency of our application.

Furthermore, we plan to investigate Galvanic Vestibular Stimulation (GVS) [37–39], which can dynamically alter users' balance perception. The lack of haptic sensation is one of the biggest limitations as described in section 8. Even though we add the screen shake to reduce this contradiction between what the participant sees and what the participant felt, but it is not enough to convince the participant that there is some force applied to their body. After the experiment, we plan to apply some hardware to our system to generate the actual shaking or balance shifting sensation to the participant. Considering the cost and compatibility with VR HMD, we choose to combine the GVS to our system because Misha et al. [38] have already proved that the GVS can enhance the VR experience. We expect it to compensate for the lack of haptic sensation in our system without the need to physically shake users. The increasing trend of using virtual reality leads to several VR earthquake safety training systems. Lindero Edutainment [1] takes full advantage of VR technology to create an earthquake safety training VR-based game on Steam. The game includes all major traditional safety training procedures, from providing basic knowledge, earthquake emergency kit preparation, to the earthquake scenario display. When starting the game, the player will begin in the ordinary western style house with a TV in front of them. The TV will present the earthquake prevention guide video to the player. Then, The player has to do the emergency kit preparation task by dragging all the specific objects required for the emergency kit to the box with the controller. After completing the preparation, the player will be guided to the safe spot which in this case is under the table, and the player is suggested to actually crawl on the ground. The shaking motion of the earthquake in this game is the conventional shake in circular motion applied to the player's head.

9. Conclusion

We proposed an AR earthquake simulation experience for a consumer-grade headset using a novel AR screen shake technique. We examined its effectiveness through a user study that compared three conditions: VR, AR without the screen shake technique, and AR with the screen shake technique. As a result of the experiment, we found that the AR screen shake can increase presence and believability of the earthquake in users. It can likely improve the user's awareness during real disaster scenarios as well. We also found some evidence indicating an effect of the technique on users' balance, even though we did not supply any real sensory input to accompany the earthquake. We think that this way of using AR for virtual trainings also opens more possibilities for other kinds of disaster trainings, such as volcanic eruptions and hurricanes.

Acknowledgements

I am sincerely grateful to all of my advisers, Prof. Kiyoshi Kiyokawa, Assoc. Prof. Hideaki Uchiyama, and Assis. Prof. Naoya Isoyama. I want to express my gratitude for the constant support and encouragement from them. I very much appreciate the help from my co-authors, Mr. Johannes Schirm and Assis. Prof. Diego Vilela Monteiro. I consider it an honor to work with them on the path towards my master degree. I would like to extend my sincere thanks to Prof. Hirokazu Kato. As my co-supervisor, he had spent much time listening to my research and gave me useful feedback.

Besides, I would like to thank all my lab members, who always take their pleasure to help me in my life and study. In addition, I would like to thanks the JASSO scholarship, and the tuition exemption of NAIST. These financial supports significantly help my study in Japan. Without them, I may not be able to focus on my research. Many thanks again.

Above ground, My biggest thanks to my family. This thesis is dedicated to my parents who have always stood by me and showered me with their love.

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