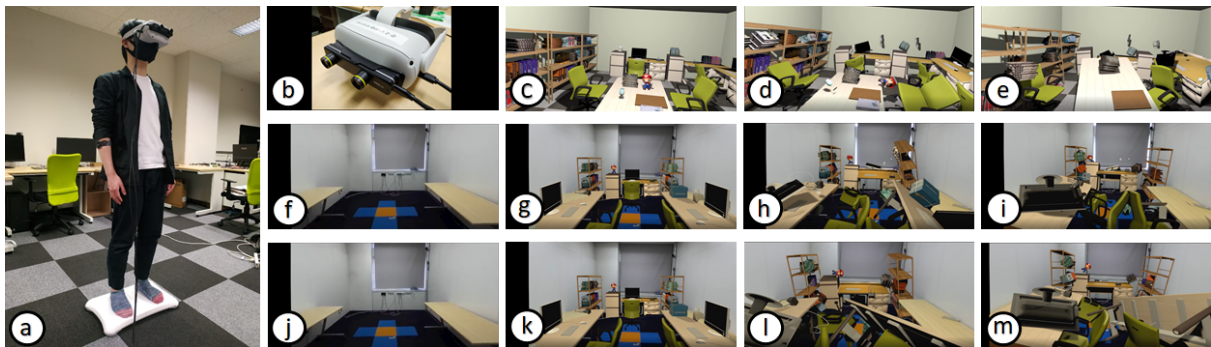# Compelling AR Earthquake Simulation with AR Screen Shaking

S. Chotchaicharin[1†] and J. Schirm[‡1] and N. Isoyama[§1] and D. V. Monteiro[¶1] and H. Uchiyama[∥1] and N. Sakata[**1] and K. Kiyokawa[1††]

Figure 1: *Configurations of our experiment. Participants stand on a Wii Balance Board (a) and wear an Oculus Quest 2 headset with a ZED Mini camera attachment (b). They experience a simulated earthquake in three visual conditions; VR (c - e), AR without the AR screen shake technique (f - i), and AR with the AR screen shake technique (j - m). f and j are identical images of a real room before augmentation. c, g and k are the initial views in each condition before the simulated earthquake. d, h, l and e, i and m are typical views in each condition at the same timings. Note that the entire view is being shaken by simulating applied force to the user's head in l and m with our AR screen shake technique (please refer to the supplemental video), which was found to be effective for a more compelling earthquake experience.*

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.

CCS Concepts

*• **Human-centered computing** → **Mixed / augmented reality; Virtual reality;** User studies; • **Computing methodologies** → Real-time simulation;*

---

† e-mail:chotchaicharin.setthawut.cs6@is.naist.jp

‡ e-mail:schirm.johannes.sh6@is.naist.jp

§ e-mail:isoyama@is.naist.jp

¶ e-mail:Diego.Vilela-Monteiro@liverpool.ac.uk

∥ e-mail:hideaki.uchiyama@is.naist.jp

** e-mail:sakata@rins.ryukoku.ac.jp

†† e-mail:kiyo@is.naist.jp

1. Introduction

Many countries 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 [LLQ*17]. 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) [CMM*11, Yan74]. The common training procedure includes reading a safety manual [Sch05, Gra01], 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 [CMM*11, Yan74, Gra01]. **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 lead to several VR earthquake safety training systems. Lindero Edutainment [Edu17] takes the full advantage of VR technology to create an earthquake safety training 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. Li et al. [LLQ*17] and Suzuki et al. [SIQ*18] also use VR to develop an earthquake safety training for research purposes. Some of the earthquake safety trainings even include an evacuation training such as Sudiarno et al. [S*20]. 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. 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.

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. [JCJ16] 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. Yamashita et al. [YTS12] also use the AR for earthquake learning support through mobile devices. On the other hand, Mitsuhara et al. [MIS17] use the AR for designing the training program for disaster prevention trainers to instruct the trainee properly with voice-based interaction.

Wang et al. [WDL*14] 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 [MSM*16]. 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. [MPRS21] used the optical see-through approach to create an AR simulation experience with the Hololens headset and Pfeil et al. [PMB*21] 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, i.e., they cannot simulate unintended camera motion induced by the earthquake. In this work, we create an AR-based earthquake simulation to address this problem by using the video see-through approach with an Oculus Quest 2 headset and a ZED Mini camera attachment.

3. AR Screen Shake

We try to simulate the user's view in the earthquake incident, also taking the force applied to their head into consideration. It is simple to manipulate the user's view in VR, 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 on to 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, considering the applied force. 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.
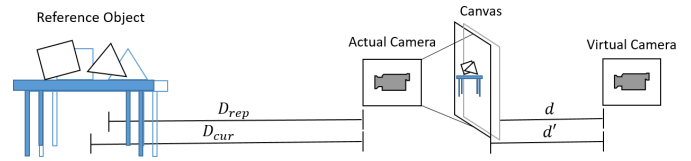
Figure 2: *The setup of the AR screen shake technique. The rendered image from the first pass is displayed on a virtual canvas, which is then captured by the virtual camera in the second pass. A reference object is away from the user's position by the representative distance D_{rep} before the force is applied, and by the current distance D_{cur} after the force is applied. This transfers to a distance between the virtual camera and the canvas of d before, and d' after the force is applied.*

Figure 2 shows how the AR screen shake is rendered. It shows how for each frame, D_{rep} and D_{cur} are used to determine the desired displacement (before and after simulating force application to the user's head) and appropriately adjust d and d' of the virtual rendering setup. The idea to define the value of d' is that the apparent size of the reference object needs to be consistent between the two rendering passes. Hence, the distance ratios $\frac{d'}{d}$ and $\frac{D_{cur}}{D_{rep}}$ must be the same. d' can be simply acquired using equation 1:

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

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 3 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. Figure 4 shows six example perspectives comparing the simulated actual camera and the virtual camera in our technique. We can confirm that our technique generally yields 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
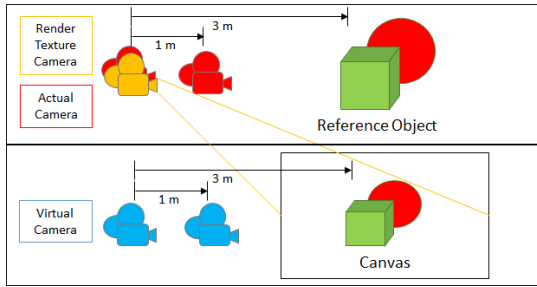
Figure 3: *Configurations for the example views. A green cube (reference object) is 3 meters away from the actual camera. A sphere is behind the green cube. The two objects are rendered by the actual camera in the first rendering pass, displayed on the canvas, and then again rendered by the virtual camera in the second pass. We compare the views of the actual and virtual camera by moving both of them forward 1 meter.*
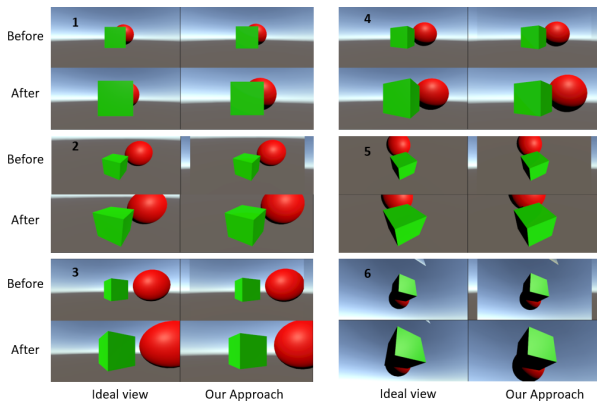
Figure 4: *Example views from the simulated actual camera and the virtual camera in our technique from 6 example perspectives. We can confirm that our technique generally yields good approximation.*

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. Then, the Rigidbody component is added to the acquired mesh to make it interactable for physics simulation in Unity.

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 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 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 interactable 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.

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. The dataset used in our study has been recorded and made publicly available by the Japan Meteorological Agency [Age20]. For a realistic simulation, the acceleration data is directly applied to the virtual room using the "RigidBody.AddForce" function of Unity's physics engine to simulate the earthquake force in all directions (NS, EW, and UD). 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 at.

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. Then, we tell the participant to rotate just their head, not the whole upper body to avoid unnecessary noise in balance data.

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.

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 [lsh20]" via Bluetooth, which recorded COP measurements at a rate of 16 Hz. The resulting data was then merged with the 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. 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 1.

From Table 1, 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 1 will be used to evaluate the effectiveness of our proposed method.

The post-questionnaire was designed to evaluate the overall ex-

Table 1: *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

perience 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 2.

Question (a) from Table 2 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

6.1. Questionnaires

We perform Aligned Ranks Transformation ANOVA analysis first to find significant differences between groups. Figure 5 shows the result of questionnaire analysis.

From Fig. 5, each sub-graph represents the summary of the answer from each item in Table 1. 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) [Hay13].

Figure 5(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 5(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 5(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

Table 2: *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
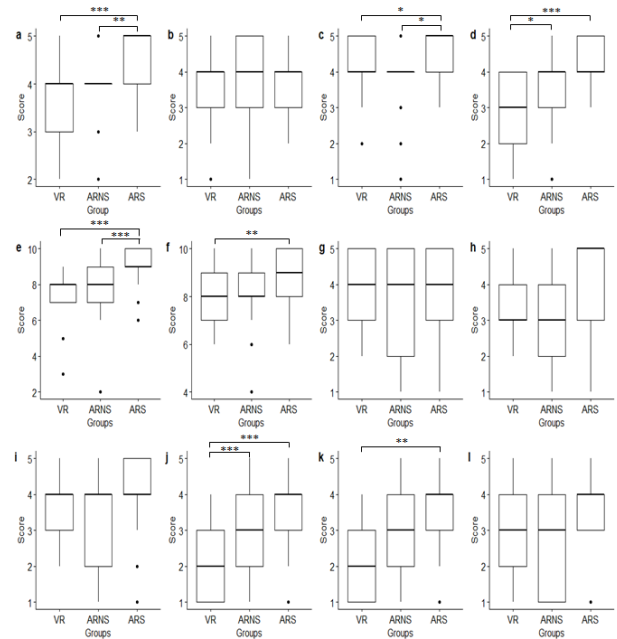
Figure 5: *A visual summary of all questionnaire answers with significance annotated by stars per category (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).*

method found SSDs between VR and ARNS ($p < 0.05$) and between VR and ARS ($p < 0.001$). Figure 5(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 5(f) shows the overall score of all three conditions comparing with the traditional training. An ANOVA found an SSD ($F_{(2,48)} = 6.1606$, $p < 0.01$) and the BH method found SSDs between VR and ARS ($p < 0.01$). Figure 5(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.

Figure 5(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 5(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. The results from Table 2(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 2(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 6 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.
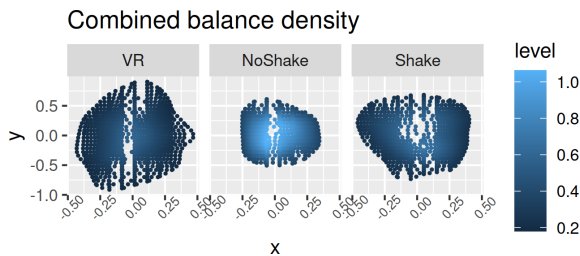
Figure 6: *Comparison of simplified density maps for the COP of all participants during earthquake movements, separated by shake condition. Units are in centimeters. Generated by extracting level points from R's **stat_density_2d()** and filtering levels below level mean per group, yielding the "core" of each density map.*

Another important aspect of COP movement is how it evolved over time. Figure 7 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.
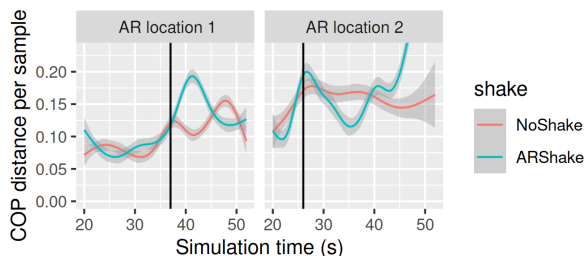
Figure 7: *Comparison of smoothed acceleration per COP sample for all participants during earthquake movements, separated by AR scene and grouped by shake condition. The black line represents the earthquake's "peak" of intensity. Units are in centimeters.*

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 8 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.
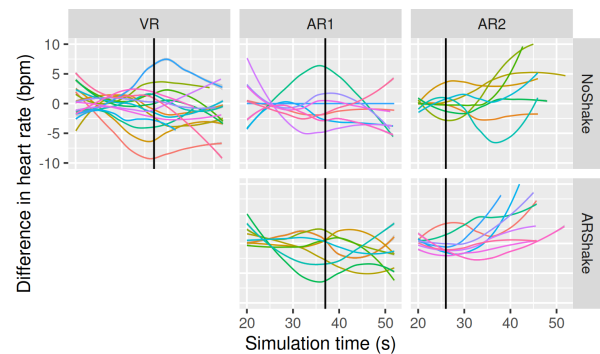
Figure 8: *Smoothed difference in heart rate per participant, starting from the first earthquake movement, separated by scene and screen shake condition. Units are in heartbeats per minute.*

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 5(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. 6. However, a quantitative analysis of the respective questionnaire item did not result in an SSD as shown in Fig. 5(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. 6, 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 [RS91].

That said, the smoothed accelerations over time shown in Fig. 7

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 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. 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 [SS00], 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. Some negative comments on this issue include "I noticed some items were not falling down" and "Neighbour items were not moving". 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 [QLHG19], 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.

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. 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.

To further develop the AR screen shake technique, we would like to improve image distortion in the second rendering pass to make it more natural. We also plan to expand the system to full-fledged earthquake preparedness and response training by integrating a realistic sound system and a user interface to teach appropriate behaviors under an earthquake. Furthermore, we plan to investigate Galvanic Vestibular Stimulation (GVS) [QXP*21, SJM19, MAA*05], which can dynamically alter users' balance perception. We expect it to compensate for the lack of haptic sensation in our system without the need to physically shake users.

References

[Age20] AGENCY J. M.: Strong motion observation data of major earthquakes. https://www.data.jma.go.jp/svd/eqev/data/kyoshin/jishin/index.html, last access: June 3 2020. 4

[CMM*11] CONTRIBUTORS R., MCCARTHY J., MCCALLISTER N., WILLIAMS R. A., ET AL.: *Putting down roots in earthquake country-Your handbook for earthquakes in the Central United States*. Tech. rep., US Geological Survey, 2011. 2

[Edu17] EDUTAINMENT L.: Earthquake simulator vr (pc version) [video game]. [Steam], 2017. 2

[Gra01] GRANT L. B.: Living with earthquakes in california: A survivor's guide. *Eos, Transactions American Geophysical Union 82* (12 2001), 611–611. doi:10.1029/01eo00354. 2

[Hay13] HAYNES W.: *Benjamini–Hochberg Method*. Springer New York, New York, NY, 2013, pp. 78–78. URL: https://doi.org/10.1007/978-1-4419-9863-7_1215, doi:10.1007/978-1-4419-9863-7_1215. 6

[JCJ16] JUNG S.-U., CHO H., JEE H.-K.: An ar-based safety training assistant in disaster for children. In *SIGGRAPH ASIA 2016 Posters*. 2016, pp. 1–2. 3

[LLQ*17] LI C., LIANG W., QUIGLEY C., ZHAO Y., YU L.-F.: Earthquake safety training through virtual drills. *IEEE transactions on visualization and computer graphics 23*, 4 (2017), 1275–1284. 2, 3

[lsh20] LSHACHAR: Wiibalancewalker. https://github.com/lshachar/WiiBalanceWalker, last access: June 3 2020. 5

[MAA*05] MAEDA T., ANDO H., AMEMIYA T., NAGAYA N., SUGIMOTO M., INAMI M.: Shaking the world: galvanic vestibular stimulation as a novel sensation interface. In *ACM SIGGRAPH 2005 Emerging technologies*. Association for Computing Machinery, New York, United States, 2005, pp. 17–es. 8

[MIS17] MITSUHARA H., IGUCHI K., SHISHIBORI M.: Using digital game, augmented reality, and head mounted displays for immediate-action commander training. *International Journal of Emerging Technologies in Learning 12*, 2 (2017). 3

[MPRS21] MORO C., PHELPS C., REDMOND P., STROMBERGA Z.: Hololens and mobile augmented reality in medical and health science education: A randomised controlled trial. *British Journal of Educational Technology 52*, 2 (2021), 680–694. doi:https://doi.org/10.1111/bjet.13049. 3

[MSM*16] MEDEIROS D., SOUSA M., MENDES D., RAPOSO A., JORGE J.: Perceiving depth: optical versus video see-through. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology* (2016), pp. 237–240. 3

[PMB*21] PFEIL K., MASNADI S., BELGA J., SERA-JOSEF J.-V. T., LAVIOLA J.: Distance perception with a video see-through head-mounted display. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (2021), pp. 1–9. 3

[QLHG19] QI C. R., LITANY O., HE K., GUIBAS L.: Deep hough voting for 3d object detection in point clouds. In *2019 IEEE/CVF International Conference on Computer Vision (ICCV)* (2019), pp. 9276–9285. doi:10.1109/ICCV.2019.00937. 8

[QXP*21] QI R. R., XIAO S. F., PAN L. L., MAO Y. Q., SU Y., WANG L. J., CAI Y. L.: Profiling of cybersickness and balance disturbance induced by virtual ship motion immersion combined with galvanic vestibular stimulation. *Applied Ergonomics 92* (4 2021), 103312. doi:10.1016/j.apergo.2020.103312. 8

[RS91] RICCIO G. E., STOFFREGEN T. A.: An ecological theory of motion sickness and postural instability. *Ecological Psychology 3*, 3 (1991), 195–240. URL: https://doi.org/10.1207/s15326969eco0303_2, arXiv:https://doi.org/10.1207/s15326969eco0303_2, doi:10.1207/s15326969eco0303_2. 7

[S*20] SUDIARNO A., ET AL.: Analysis of human factors and workloads in earthquake disaster evacuation simulations using virtual reality technology. In *IOP Conference Series: Materials Science and Engineering* (2020), vol. 1003, IOP Publishing, p. 012082. 3

[Sch05] SCHWARZENEGGER A.: *Homeowner's Guide to Earthquake Safety Before Earthquake*. The California Seismic Safety Commission State of California, 2005. 2

[SIQ*18] SUZUKI R., IITOI R., QIU Y., IWATA K., SATOH Y.: Ai-based vr earthquake simulator. In *Virtual, Augmented and Mixed Reality: Applications in Health, Cultural Heritage, and Industry* (Cham, 2018), Chen J. Y., Fragomeni G., (Eds.), Springer International Publishing, pp. 213–222. 3

[SJM19] SRA M., JAIN A., MAES P.: Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (2019), pp. 1–14. 8

[SS00] SLATER M., STEED A.: A virtual presence counter. *Presence: Teleoperators and Virtual Environments 9*, 5 (10 2000), 413–434. doi:10.1162/105474600566925. 8

[WDL*14] WANG H.-Y., DUH H. B.-L., LI N., LIN T.-J., TSAI C.-C.: An investigation of university students' collaborative inquiry learning behaviors in an augmented reality simulation and a traditional simulation. *Journal of Science Education and Technology 23*, 5 (2014), 682–691. 3

[Yan74] YANEV P. I.: *Peace of mind in earthquake country: how to save your home and life*. The Seismological Society of America, 1974. 2

[YTS12] YAMASHITA N., TAKI H., SOGA M.: A learning support environment for earthquake disaster with a simulation of furniture falling by mobile ar. In *2012 International Conference on Information Technology Based Higher Education and Training (ITHET)* (2012), IEEE, pp. 1–5. 3