Let Your World Open

CAVE-based Visualization Methods of Public Virtual Reality towards a Shareable VR Experience

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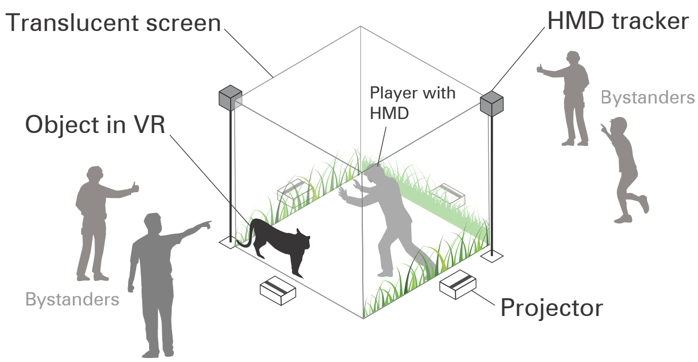

Figure 1: Left: Overview and setup of the ReverseCAVE for public VR visualization. Right: Using the ReverseCAVE, bystanders can see the HMD user (player) and the VR environment simultaneously without an HMD; bystanders can capture photographs or record videos to share with others.

ABSTRACT

Virtual reality (VR) games are currently becoming part of the public-space entertainment (e.g., VR amusement parks). Therefore, VR games should be attractive for players, as well as for bystanders. Current VR systems are still mostly focused on enhancing the experience of the head-mounted display (HMD) users; thus, bystanders without an HMD cannot enjoy the experience together with the HMD users. We propose the "*ReverseCAVE*": a proof-of-concept prototype for public VR visualization using CAVE-based projection with translucent screens for bystanders toward a shareable VR experience. The screens surround the HMD user and the VR environment is projected onto the screens. This enables the bystanders to see the HMD user and the VR environment simultaneously. We designed and implemented the ReverseCAVE, and evaluated it in terms of the degree of attention, attractiveness, enjoyment, and shareability, assuming that it is used in a public space. Thus, we can make the VR world more accessible and enhance the public VR experience of the bystanders via the ReverseCAVE.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**.

KEYWORDS

Environmental VR, mixed reality (MR), sharing experience, CAVE.

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1 INTRODUCTION

Virtual reality (VR) games with head-mounted displays (HMDs) are rapidly increasing and are becoming part of the public-space entertainments (e.g., VR amusement parks and video game expositions). According to Biocca and Levy [2], sharing VR with friends and family is more enjoyable. However, in several cases, people without an HMD cannot share the experiences of those wearing an

HMD. Therefore, in the current public-space VR entertainment age, it is important to be able to share VR experiences with bystanders.

One of the commonly employed solutions to this problem is to show the VR contents those captured from the first-person viewpoint of a player on a large display. Another alternative solution involves the use of chroma key compositing to share VR experiences through a mixed reality medium [28, 30]. By showing chroma key composed image using a display, it is possible to share the VR environment with bystanders.

As previously described, there are several manners through which VR can be shared; however, no study exists in which VR in public spaces has been explored. Therefore, in this study, we focused on the "*shareability*" of the VR contents in public spaces. To enhance the shareability, we propose the "ReverseCAVE" system, in which the experiences of the player in the VR environment (HMD user) can be shared with bystanders (non-HMD users), as shown in Figure 1. The ReverseCAVE has a cubic screen surrounding the player, similar to the CAVE [4]. The screens are translucent in order for the bystanders outside the ReverseCAVE to be able to see the player in it. The VR environment, which is experienced by the player, is projected on the screen. Thus, the bystanders can see both the real player and the VR environment experienced by the player. The CAVE is a system for a person who is inside the cubic screen. In contrast, the *Reverse*CAVE is a system for persons who are outside the cubic screen.

We wish to expose the person who is completely isolated in the VR space to the real world. In addition, we expect our system to be used in public spaces, such as conventions, video game expositions, and amusement parks (not for domestic use). This is because, for example, bystanders that wait in line to play VR games at VR game expositions may become bored. Moreover, people who pass by the VR booth may not be attracted by the VR games because they do not have knowledge of the VR contents beforehand and cannot understand how the contents are exciting. Thus, we were motivated to excite bystanders by using various visualization methods of VR games. We were inspired by open-air attractions in theme parks, such as roller coasters, which can entertain the riders, as well as the bystanders waiting in line.

In the previous papers, we present the concept of ReverseCAVE [13–15]. Following these previous work, in this paper, we will present the design of the ReverseCAVE in detail — a proof-of-concept implementation — and the results of the in-depth user studies that were conducted for the evaluation of the ReverseCAVE. To investigate how the ReverseCAVE can contribute to public-space VR, we set the following main research question: "In public-space VR, can the ReverseCAVE increase the Degree of attention, Attractiveness, Enjoyment, and Shareability?". Moreover, we conducted user studies to compare the ReverseCAVE with other similar methods. This study makes the following contributions.

- Design of the ReverseCAVE system to address the problems of shareability in VR in public spaces.
- Implementation of a proof-of-concept of the ReverseCAVE to evaluate the feasibility of the design.
- Experimental evaluation of the performance of the ReverseCAVE in public spaces.

2 RELATED WORK

We will review related work on room projection-based augmented reality (AR), the sharing of first-person videos, and the sharing of the VR experience; moreover, we will present the focus of this study.

2.1 Room Projection-based AR

Numerous research works have been conducted in which AR has been realized by projecting the virtual world on physical objects or a space in the real world (e.g., [25]). Raskar et al. proposed iLamps [24], a self-configuring hand-held projector, for environment-aware systems. Willson et al. [29] proposed steerable displays that can be used to superimpose graphics onto physical objects in the real world for AR and ubiquitous computing scenarios. IllumiRoom [16] is a system that augments the area surrounding a television with projected visualizations to enhance traditional gaming experiences. Benko et al. [1] proposed a spatial AR system that combines dynamic projection mapping, multiple perspective views, and device-less interaction. In addition, there are systems that transform any room into an immersive and augmented entertainment environment [17] and an AR-based telepresence system [22] using room projection.

These approaches can be used for the sharing of the VR experience; in our study, we used an approach that is similar to the aforementioned. Compared with HMD-based AR (e.g., Microsoft HoloLens) or a smartphone-based AR, room projection-based AR has certain advantages: (1) users can experience AR without any additional wearable equipment, and (2) the wider area of the content is visible because room projection-based AR is not affected by other than the human viewing angle. Therefore, room projection-based AR is suited for the scenario of publicly sharing VR contents in spaces where there is a large number of bystanders.

2.2 Sharing a First-Person Video

Parallel Eyes [18] is a system through which first-person viewpoints can be shared with others simultaneously by using HMDs and cameras. This system investigates what type of influence will happen by sharing plural first-person viewpoints in the real world. Furthermore, the concept of sharing first-person videos has been explored from various aspects [5, 6, 11, 12, 19, 20, 23].

On the other hand, we aim to observe the person who is experiencing VR and the VR contents simultaneously from a third perspective, not the first-person viewpoint of the player. By observing the player from a third-person perspective, the observer can understand both the situation in which the player is and the background. Moreover, by using the third-person perspective, the influence of motion sickness could be reduced because the screen does not change according to the movement of the player.

2.3 Sharing the VR Experience

This topic is most relevant to our study. Research on sharing the VR experience with others can be categorized into two types: (1) only displaying the situation of the VR experience (non-participative, bystanders do not participate in the game), and (2) both parties engage with the VR together (participative, bystanders participate in the game).

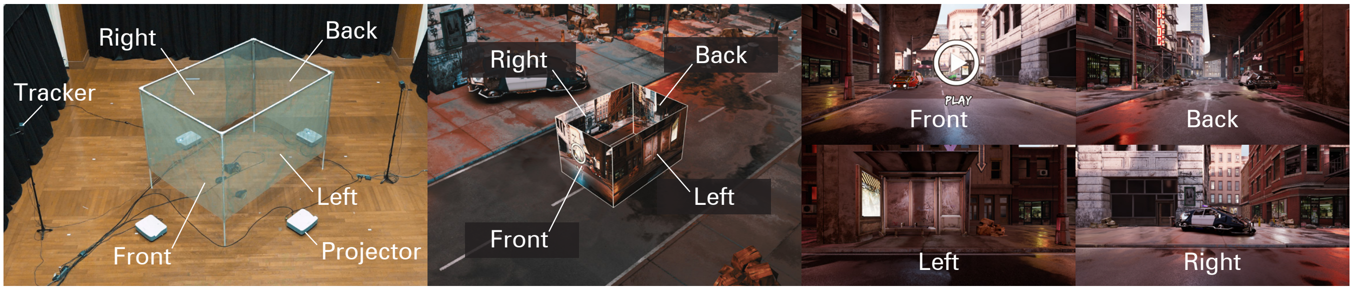

Figure 2: Relationships between four cameras and each screen for VR projection. Left: Setup of the ReverseCAVE with a cubic screen. Middle: Captured cubic image for projection (placed on the VR environment for explanation). Right: Rendered images for each screen plane.

2.3.1 *Non-participative Approach.*

SAVE [30] is a system that enables sharing the experience of people in the VR environment with those who are outside the VR environment by combining the Kinect depth camera and the tracking system of the HTC Vive. By using the viewpoint of the Kinect camera and the positional relationship of the player, it generates the third-person viewpoint image of the VR environment that the player is actually experiencing. TransparentHMD [21] is a system that enables bystanders to see the face of the HMD users. Moreover, FrontFace [3] is a system for communication between the HMD user and the non-HMD user using a smartphone attached on an HMD. This provides the eye gaze information of an HMD user to the bystanders (non-HMD users) for reducing the communication barrier between them. The ReverseCAVE is categorized into non-participative approach as well.

2.3.2 *Participative Approach.*

ShareVR [7] enables asymmetric interactions between an HMD user and non-HMD users by employing floor projection of the VR and a trackable hand-held monitor. Furthermore, research work exists on the sharing of the VR experience with others by using an additional HMD [9]. A VR system has been proposed with concurrent tele-collaboration among avatars controlled by and synchronized with multiple users in remote places using multiple HMDs. Hagler et al. [10] proposed a system that enabled bystanders to participate in the VR contents using a smartphone. The Maze Commander [26] enables asymmetric interaction between an HMD user and non-HMD users using the Sifteo Cubes. In addition, FaceDisplay [8] enables asymmetric interaction between an HMD user and non-HMD bystanders using a modified HMD that consists of three touch screens and a depth camera attached to its back. Bystanders can understand the VR environment through the screens and can participate in engaging with the VR contents via touch or gestures.

2.4 Focus of This Study

The ReverseCAVE is a non-participative approach for the sharing of the VR experience in public spaces. We were inspired by open-air attractions, such as roller coasters, which can entertain the riders, as well as the bystanders waiting in line. Such open-air attractions function as a type of advertisement. The ReverseCAVE can display the actual VR environment to the real world to attract the attention of bystanders. In addition, the ReverseCAVE enables and facilitates shooting photographs with wider variety of aspects because it adopts a cubic screen.

It should be noted that the interaction between the player and the bystanders is not so important in public VR experiences because in many cases at video game expositions, they are not acquainted with one another. Consequently, the ReverseCAVE does not have interactive features.

3 REVERSECAVE

The ReverseCAVE is a system for sharing the VR experiences of the player with bystanders. In the past study [14, 15], we used the motion capture system to acquire the position of the observer in order to calculate the projection position to maintain visual consistency for bystanders. However, bystanders are required to wear markers in order to use the motion capture system. In addition, in the conventional system, only one person can experience a fine display of the VR environment in terms of the precise perspective and consistency. We assume that the ReverseCAVE is used in public spaces and there are a lot of bystanders, therefore, we decided not to use the motion capture system to track them.

3.1 Screen

Our aim is to let the bystanders see both the actual appearance of the player and the VR environment that the player is experiencing. Therefore, the following conditions are necessary.

- In addition to the VR environment, the player himself/herself must blend into the VR world.
- The player should be visible from bystanders, not be hidden by surrounding equipment.

To fulfill the above conditions, we adopted a method of surrounding the four sides of the player using translucent screens and projecting the VR environment on the screens. By using translucent cloths for the screen, it is possible to create screens of various shapes, such as rectangular or cylindrical shapes. In this study, as a proof-of-concept implementation, we used the cubic screen because it was easy to assemble.

3.2 Projection

In the ReverseCAVE, the VR environment that the player is experiencing is projected on the screens, as shown in Figure 1. We mounted four virtual cameras on the head of the player in the VR

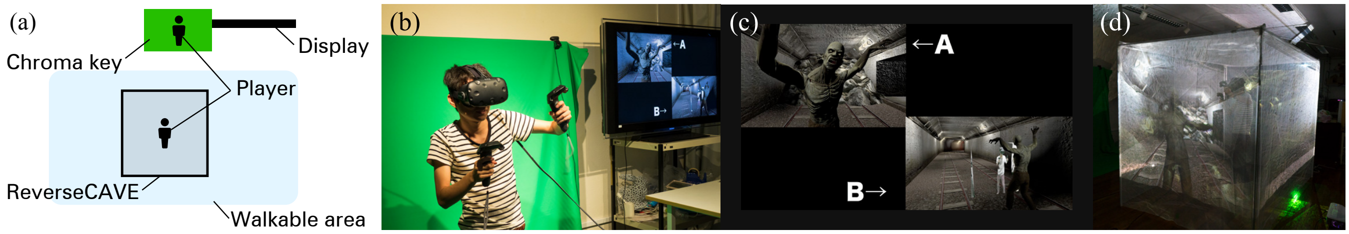

Figure 3: Setup of Study 1. (a) Layout of the VR game booths. Participants walk around in the walkable area and see the VR booths. (b) First-person view (FPV) and Chroma key. (c) Contents of the display. (d) ReverseCAVE.

software (Figure 2). Each of the four cameras was aligned along each of the screen's cardinal directions (front, back, left, and right) to capture the VR environment and to project it on the cubic screen (four translucent walls). The images recorded with each virtual camera are projected on the screens with each projector.

3.3 Equipment

The equipment we used to demonstrate the proof-of-concept was the following. As the cubic screen, we used a white mosquito net, which is a translucent roughly knit cloth with resin fibers (diameter of approximately 0.2 mm). It is a material that diffusely reflects images moderately, and can be looked through from one side to the other side. By using this screen, we could simultaneously see the images projected on the screens and observe the player inside the cubic screen. The projector was the OPTOMA EH320UST, which is a high-intensity short-focus projector. The resolution was 1920×1080 pixels and the brightness was 4,000 lm. Each projector was placed against each of the four walls of the cubic screen. One computer was utilized to operate the ReverseCAVE, while driving the projection and the VR system. The computer had an Intel Core i7-6700K processor, 32 GB of memory, and two NVIDIA GeForce GTX 1080 graphics boards. Unity (game engine) was used for the creation of the projected images of the ReverseCAVE.

4 STUDY 1: THE DEGREE OF ATTENTION, ATTRACTIVENESS, ENJOYMENT, AND SHAREABILITY

Assuming that the ReverseCAVE is used in public spaces (e.g., video game expositions), we evaluated it in terms of the degree of attention, attractiveness, enjoyment, and shareability by comparing it with conventional methods for the visualization of VR games. We created an exhibition area for video game expositions in the meeting room. The floor layout is shown in Figure 3a. We demonstrated a zombie VR game (the player fights against the zombie), which we created with Unity and Steam VR by using three visualization methods: the first-person view (FPV), the Chroma key, and the ReverseCAVE. Then, the participants evaluated the three sharing methods in terms of the four aforementioned aspects as visitors of a video game exposition.

4.1 Study Design

The study was conducted using a repeated measures design with one independent variable. The independent variable was the visualization method (*FPV, Chroma key, ReverseCAVE*). The FPV is the most basic method for the visualization of VR contents. The FPV displays the first-person view of the player on a large TV monitor (Figure 3b). The Chroma key is the synthesis method in which a green screen is used for the capturing of the player who is standing in front of the green screen; the player is superimposed onto the VR environment [28, 30]. Participants would achieve a more spatial representation of the virtual environment. We used a web camera (Logicool C270 HD Webcam, 1280×720 pixels, 30 fps) to capture the player and Chroma Key Kit plugin of Unity [27] to implement the Chroma key. The visualization via the FPV and the Chroma key was prerecorded and displayed on a single display to keep consistency within the participants, as shown in Figure 3c.

We created questionnaires related to the degree of attention, attractiveness, enjoyment, and shareability, which were rated on a 5-point Likert scale. The participants rated each visualization method and justified their rating.

4.2 Procedure

The study was conducted in a university meeting room. The room was dim for the purposes of projection. The participants participated in the study as visitors at a video game exposition. After a brief introduction, the participants answered a demographics questionnaire. Then, our staff began to play the zombie VR game at each exhibition booth and the participants began the evaluation of the visualization methods as visitors of a video game exposition. The participants were asked to walk around to observe each exhibition booth freely and to complete the questionnaires related to the visualization methods. We informed the participants that whether the content was good or bad was entirely irrelevant to the evaluation; therefore, we asked them to evaluate solely the visualization method, and not the content. Until the participants completed to fill the questionnaires, our staff continued to play the VR game. The study required 33 min on average and the participants received a 500 JPY Amazon gift code (approximately 4.5 USD).

4.3 Participants and Apparatus

Ten participants (1 female and 9 males), aged between 21 and 26 years (M = 23.2, SD = 1.3) were recruited for participation in the experiment. Three participants had normal vision, seven participants had corrected vision, six wore glasses, and one wore contact lenses.

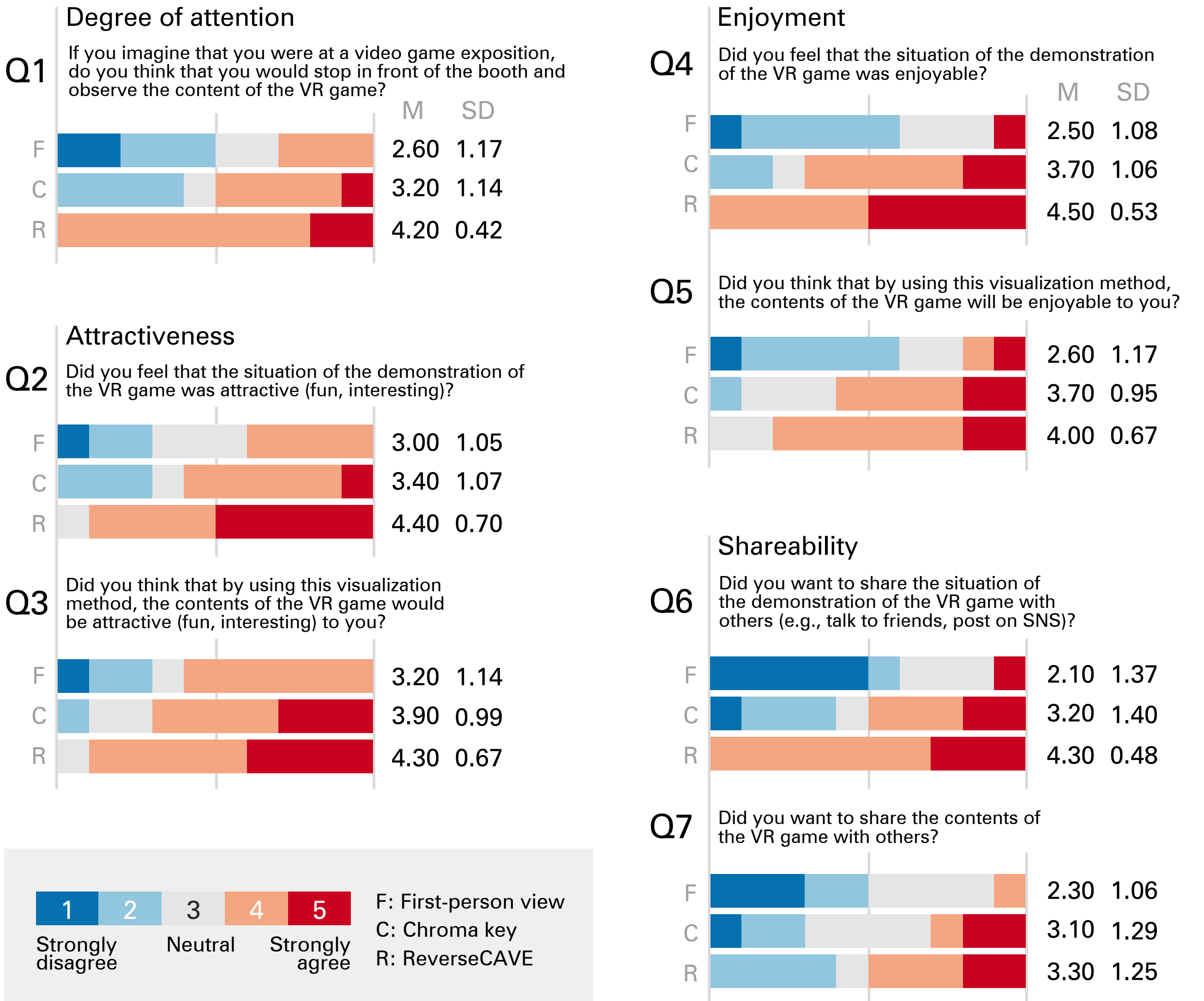

Figure 4: Results of Study 1 (5-point Likert scale).

They had an average experience with VR devices of 1.2 months (SD = 2.6). Their average interest in VR technology was very high (M = 4.0, SD = 1.2) and their average motivation to play VR games in the following 12 months was very high as well (M = 4.0, SD = 1.2). All results were measured on a 5-point Likert scales.

In the experiment, we used the same equipment described in Section 3.3 for the ReverseCAVE, as shown in Figure 3d. For the FPV and the Chroma key, we used a SONY BRAVIA FHD TV (KDL-52X5050, 52 inch) to display the VR environment. Two videos were shown on one TV monitor, therefore, each video was scaled to 26 inch.

4.4 Result

The scores that each visualization method received are illustrated in Figure 4. We analyzed the results of the Likert scale scores with a Friedman test at a significance level of 5%. The independent variable was the visualization methods and the dependent variable was the Likert scale score of each questionnaire.

4.4.1 Degree of Attention. For Q1, a Friedman test revealed that the ratings were significantly affected by the visualization method ($\chi_{(2)} = 12.20$, $p < 0.01$). The post-hoc test revealed that the *ReverseCAVE* was rated significantly higher in terms of attention than the *FPV* ($p < 0.01$).

4.4.2 Attractiveness. For Q2 and Q3, a Friedman test revealed that the ratings were significantly affected by the visualization method (Q2: $\chi_{(2)} = 9.74$, $p < 0.01$, Q3: $\chi_{(2)} = 9.19$, $p < 0.05$). The post-hoc test revealed that the *ReverseCAVE* was rated significantly higher with respect to attractiveness both in terms of the situation (Q2) and the content (Q3) than the *FPV* (Q2: $p < 0.05$, Q3: $p < 0.05$).

4.4.3 Enjoyment. For Q4 and Q5, a Friedman test revealed that the ratings were significantly affected by the visualization method (Q4:

$\chi_{(2)} = 11.41$, $p < 0.01$, Q5: $\chi_{(2)} = 11.08$, $p < 0.01$). The post-hoc test revealed that the *ReverseCAVE* was rated as significantly more enjoyable both in terms of the situation (Q4) and the content (Q5) than the *FPV* (Q4: $p < 0.01$, Q5: $p < 0.05$).

4.4.4 Shareability. For Q6, a Friedman test revealed that the ratings were significantly affected by the visualization method ($\chi_{(2)} = 11.53$, $p < 0.01$). The post-hoc test revealed that the *ReverseCAVE* was rated as significantly more shareable in terms of the situation than the *FPV* (Q4: $p < 0.01$). For Q7, there was no significant difference among the visualization methods ($\chi_{(2)} = 5.85$, $p = 0.05$).

5 STUDY 2: SHAREABILITY ON SOCIAL NETWORKING SERVICES (SNSS)

In Study 1, the ReverseCAVE was prone to achieve the most positive rating than other methods; however, there were no significant differences between the *Chroma key* and the *ReverseCAVE*. Therefore, to gain insight on the shareability of each method on SNSs, we organized a workshop of photo shoot on VR games in public spaces for the purpose of sharing photographs on SNSs (e.g., Facebook, Twitter, Instagram) and we explored the differences among the photographs that were captured for each visualization method. We installed an exhibition area for a video game exposition in the public space of the university, as shown in Figure 5. We demonstrated the same VR game in Study 1 using the *Chroma key* and the *ReverseCAVE*. Then, participants captured photographs of the situation in order to freely share them on SNSs as visitors at the video game exposition. We observed the photographs from two viewpoints: the sharing context and the spatial variety of the shots.

5.1 Study Design

We used two visualization methods: the *Chroma key* and the *ReverseCAVE*. We divided participants into two groups: one group captured SNS photographs of the VR game with the *Chroma key* and the other group captured photographs of the VR game with the *ReverseCAVE*.

5.2 Procedure

The study was conducted in a university public space. The participants participated in the study as visitors at a video game exposition. After a brief introduction, our staff started playing the zombie VR game at the exhibition booth. The participants were told to capture photographs of the VR games and freely share them on SNSs. To simulate a more realistic situation, we designed the study in order for the participants to feel as if they visited a video game exposition with their friend; we instructed the participants to imagine that our staff who was playing the VR game was their friend. After the participants completed the task of capturing SNS photographs, we asked them to type a text as a post (e.g., a tweet accompanying the photograph). We asked the participants to make a post as they would normally do; thus, we allowed any photograph processing (e.g., color filter on Instagram). The study required an average of 8 min.

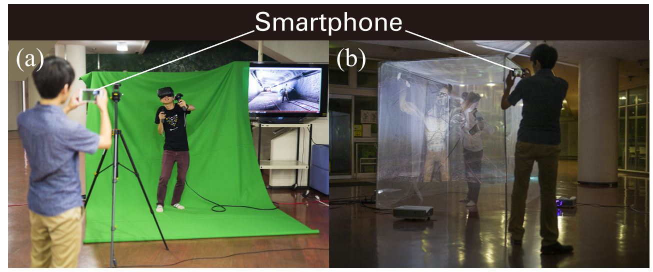

Figure 5: Setup of Study 2. (a) Chroma key. (b) ReverseCAVE. The participants captured photographs of the situation (their friend was playing the VR games) to freely share on SNSs as a visitor at a video game exposition. Then, they typed a text to be shared together with the photograph.

5.3 Participants and Apparatus

Twelve participants (2 females and 10 males) aged between 18 and 24 years (M = 21.3, SD = 1.7) participated in the experiment. They were majoring in computer science. These participants did not participate in Study 1. We used the same apparatus as in Study 1, and we only showed the real time Chroma key composed image on a TV monitor (SONY BRAVIA FHD TV KDL-52X5050, 52 inch).

5.4 Result

The photographs captured by the participants are shown in Figure 6. We evaluated the SNS photographs from two viewpoints: the sharing context and the spatial variety of the shots.

5.4.1 Sharing Context. With the *Chroma key* method, we observed that participants mainly focused on and emphasized the VR player when they were capturing the photographs, and they were not eager to shoot the content itself. Three of six participants mainly captured the VR player (P1, P2, P3). On the other hand, with the *ReverseCAVE*, the participants were focused both on the VR player and the VR environment.

5.4.2 Variety of Shots. With the *Chroma key* method, the participants made efforts to capture photographs that included both the VR player and the TV display in the same frame, in front of the player. In contrast, with the *ReverseCAVE*, the participants were eager to walk around the cubic screen to find the best angle to capture a photograph, and the variety of the viewpoints of the photographs was wider than that of the Chroma key photographs. With the *ReverseCAVE*, the photographs were taken from not only the front side but also the back side of the player. Four of six photographs were taken from back side of the player (P7, P9, P10, P11), which is unique to the *ReverseCAVE* condition.

6 DISCUSSIONS

In the Study 1, we asked participants to state their feelings in the form of free writing. Participant 1 (P1) commented "*I felt that it was difficult to completely understand the VR contents via the information from only the FPV or the Chroma key. On the other hand, I felt that the ReverseCAVE clearly informed me about both the player's view and feelings, so this is better for understanding the situation.*" P5

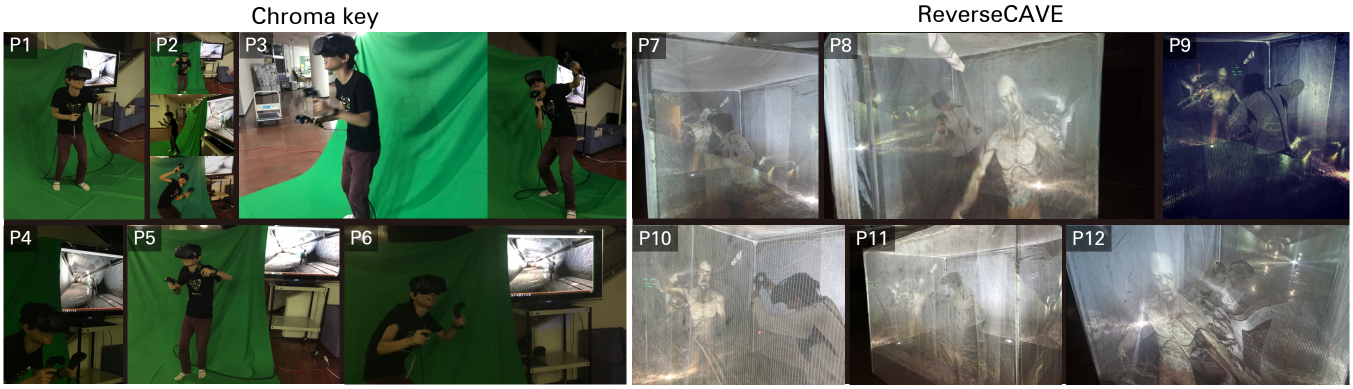

Figure 6: Result of Study 2. Each text accompanying the photograph as a post was as follows. P1: Blank. P2: "*Awesome!!*" P3: "*[Friend name] looks like fun XD.*" P4: "*He is fighting, but he is going to lose. #vr*" P5: "*[Friend name] is fighting now.*" P6: "*What is this!? so funny lol.*" P7: "*[Friend name] is awesome.*" P8: "*Hey! This is new zombie game!*" P9: "*Zombie and a man.*" P10: "*Wow, he looks too weak. lol. [Friend name] is the no.1 person who is definitely knocked down when a zombie comes.*" P11: "*Fighting [Friend name].*" P12: "*He's really scared of the zombie. lol.*"

commented "*Usually, I feel strange in cases where the player wears an HMD, but I actually didn't feel strange at all this time (with the ReverseCAVE).*" According to these comments, the ReverseCAVE has an advantage in terms of sharing and visualization of the VR contents.

Meanwhile, certain shortcomings were pointed out. P8 commented "*I like the ReverseCAVE better than the other methods, but the player was slightly obscure because the environment was dark.*" P10 commented "*[...] I've never seen anything like this (the ReverseCAVE) before and it felt interesting in terms of being able to directly see the player through the virtual image, but the image is slightly low-contrast and it felt somewhat unpleasant because the display is cubic; not truly* 360° *(cylindrical) [...].*" The ReverseCAVE needs for the environment to be moderately dark because of the projection. The light of projectors can be used as the lighting of the player. This enables the bystanders to see the player in dark rooms. However, this lighting depends on the brightness of the projected content. In the experiment, we used the zombie VR game, in which the brightness of the stage was relatively low. To solve this problem, we plan to use a different light source for the lighting of the player (e.g., install LEDs in the frames of the cubic screen).

From Study 1, we obtained an interesting result. Regarding the shareability, the ratings of Q6 and Q7 were similar for the *FPV* and the *Chroma key*. However, for the *ReverseCAVE*, the ratings of Q6 and Q7 were not similar and the rating of Q7 was lower. P3 commented "*I think that the topic of the visualization method (ReverseCAVE) might come up first in a conversation. The topic of the VR content is not as likely to come up in a conversation.*" P10 commented "*The visualization method (ReverseCAVE) may catch a great deal of attention and people might be not interested in the VR content very much.*" The ReverseCAVE is an eccentric and appealing visualization method; therefore, sometimes the ReverseCAVE is more prominent and appealing than the VR contents.

7 LIMITATIONS AND FUTURE WORK

Because the ReverseCAVE requires the player to be enclosed within the translucent screens, the movement of the player is limited. Therefore, VR contents which require wider space are difficult to be applied to our current system. On the other hand, contents that require narrower spaces, such as games in video game expositions or advertisement demonstrations, are suitable for application to the ReverseCAVE.

Moreover, our system employs a short-focus digital light processing (DLP) projector, the light source of which generates high brightness. However, the ReverseCAVE requires a moderately dark environment in order for appropriate projection luminance to be maintained.

In the future, we will explore the transparency and open (non-screen) area of the surrounding screen to study how these parameters effect the bystanders' impression. For example, we will compare impressions of bystanders when they observe the VR player surrounded by three displays from one open side with the impressions of this study.

We also plan to increase the number of contents and participants to normalize these effects. We will test compatibility between the VR visualization methods and the displayed contents.

We simulated a VR game exposition in a public space for our user studies; thus, the result obtained may be limited. Therefore, we will conduct further user studies at real public spaces in order to verify that the results of the present work are in agreement with the results obtained at real public spaces.

8 CONCLUSION

In this work, the ReverseCAVE was presented, which is a proof-of-concept prototype for public VR visualization using a CAVE-based projection with translucent screens to achieve a shareable VR experience with the bystanders. In this paper, a proof-of-concept implementation of the ReverseCAVE was presented and user studies were conducted to evaluate the ReverseCAVE. First, we considered the focus of this study and proposed that the ReverseCAVE would be suitable for public-space VR. Under the above assumption, we evaluated the ReverseCAVE by comparing with conventional methods and we explored four different aspects for each visualization method in a video game exposition. As a result, the chroma key compositing (existing method) and the ReverseCAVE were preferred in the context of sharing VR experiences in public spaces. Finally, we organized a workshop of VR games photo shoot for SNSs and explored the differences among the photographs that were captured for each visualization method. As a result, with the ReverseCAVE, the participants were more motivated to capture photographs with a wide variety of angles and viewpoints than with the chroma key compositing, and captured a higher number of photographs that included both the player and the contents. Consequently, the ReverseCAVE increased the degree of attention, attractiveness, enjoyment, and shareability in public VR experiences and enabled the sharing of the VR environment in an engaging and interesting manner.

REFERENCES

[1] Hrvoje Benko, Andrew D. Wilson, and Federico Zannier. 2014. Dyadic Projected Spatial Augmented Reality. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 645–655. https://doi.org/10.1145/2642918.2647402

[2] Frank Biocca and Mark R. Levy. 1995. *Communication in the Age of Virtual Reality.* Routledge.

[3] Liwei Chan and Kouta Minamizawa. 2017. FrontFace: Facilitating Communication Between HMD Users and Outsiders Using Front-facing-screen HMDs. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '17)*. ACM, New York, NY, USA, Article 22, 5 pages. https://doi.org/10.1145/3098279.3098548

[4] Carolina Cruz-Neira, Daniel J. Sandin, and Thomas A. DeFanti. 1993. Surround-screen Projection-based Virtual Reality: The Design and Implementation of the CAVE. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '93)*. ACM, New York, NY, USA, 135–142. https://doi.org/10.1145/166117.166134

[5] Susan R. Fussell, Leslie D. Setlock, and Robert E. Kraut. 2003. Effects of Head-mounted and Scene-oriented Video Systems on Remote Collaboration on Physical Tasks. In *Proceedings of the 2013 CHI Conference on Human Factors in Computing Systems (CHI '03)*. ACM, New York, NY, USA, 513–520. https://doi.org/10.1145/642611.642701

[6] Ken Goldberg, Dezhen Song, and Anthony Levandowski. 2003. Collaborative Teleoperation using Networked Spatial Dynamic Voting. *Proc. IEEE* 91, 3 (Mar 2003), 430–439. https://doi.org/10.1109/JPROC.2003.809209

[7] Jan Gugenheimer, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. 2017. ShareVR: Enabling Co-Located Experiences for Virtual Reality Between HMD and Non-HMD Users. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 4021–4033. https://doi.org/10.1145/3025453.3025683

[8] Jan Gugenheimer, Evgeny Stemasov, Harpreet Sareen, and Enrico Rukzio. 2018. FaceDisplay: Towards Asymmetric Multi-User Interaction for Nomadic Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 54, 13 pages. https://doi.org/10.1145/3173574.3173628

[9] Gyutae Ha, Hojun Lee, Sangho Lee, Jaekwang Cha, and Shiho Kim. 2016. A VR Serious Game for Fire Evacuation Drill with Synchronized Tele-collaboration Among Users. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*. ACM, New York, NY, USA, 301–302. https://doi.org/10.1145/2993369.2996306

[10] Juergen Hagler, Michael Lankes, and Andrea Aschauer. 2018. The Virtual House of Medusa: Playful Co-located Virtual Archaeology. In *FH Forschungsforum 2018 (FFH '18)*. Salzburg, ÃŰsterreich, 1–8.

[11] Tobias HÃűllerer, Steven Feiner, Tachio Terauchi, Gus Rashid, and Drexel Hallaway. 1999. Exploring MARS: Developing Indoor and Outdoor User Interfaces to a Mobile Augmented Reality System. *Computers and Graphics* 23 (1999), 779–785.

[12] Hiroyuki Iizuka, Daisuke Kondo, Hiroki Kawasaki, Hideyuki Ando, and Taro Maeda. 2011. Coordinated Behavior Between Visually Coupled Dyads. In *Proceedings of the 2nd Augmented Human International Conference (AH '11)*. ACM, New York, NY, USA, Article 23, 4 pages. https://doi.org/10.1145/1959826.1959849

[13] Akira Ishii, Ippei Suzuki, Masaya Tsuruta, Shuta Nakamae, Junichi Suzuki, and Yoichi Ochiai. 2018. ReverseCAVE: CAVE-based Visualization Methods of Public VR Towards Shareable VR Experience. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article VS01, 1 pages. https://doi.org/10.1145/3170427.3186593

[14] Akira Ishii, Masaya Tsuruta, Ippei Suzuki, Shuta Nakamae, Tatsuya Minagawa, Junichi Suzuki, and Yoichi Ochiai. 2017. ReverseCAVE Experience: Providing Reverse Perspectives for Sharing VR Experience. In *SIGGRAPH Asia 2017 VR Showcase (SA '17)*. ACM, New York, NY, USA, Article 9, 2 pages. https://doi.org/10.1145/3139468.3139482

[15] Akira Ishii, Masaya Tsuruta, Ippei Suzuki, Shuta Nakamae, Tatsuya Minagawa, Junichi Suzuki, and Yoichi Ochiai. 2017. ReverseCAVE: Providing Reverse Perspectives for Sharing VR Experience. In *ACM SIGGRAPH 2017 Posters (SIGGRAPH '17)*. ACM, New York, NY, USA, Article 28, 2 pages. https://doi.org/10.1145/3102163.3102208

[16] Andrew Jones, Ian McDowall, Hideshi Yamada, Mark Bolas, and Paul Debevec. 2007. Rendering for an Interactive 360° Light Field Display. *ACM Transactions on Graphics.* 26, 3, Article 40 (July 2007). https://doi.org/10.1145/1276377.1276427

[17] Brett Jones, Rajinder Sodhi, Michael Murdock, Ravish Mehra, Hrvoje Benko, Andrew Wilson, Eyal Ofek, Blair MacIntyre, Nikunj Raghuvanshi, and Lior Shapira. 2014. RoomAlive: Magical Experiences Enabled by Scalable, Adaptive Projector-camera Units. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 637–644. https://doi.org/10.1145/2642918.2647383

[18] Shunichi Kasahara, Mitsuhito Ando, Kiyoshi Suganuma, and Jun Rekimoto. 2016. Parallel Eyes: Exploring Human Capability and Behaviors with Paralleled First Person View Sharing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1561–1572. https://doi.org/10.1145/2858036.2858495

[19] Shunichi Kasahara and Jun Rekimoto. 2014. JackIn: Integrating First-person View with Out-of-body Vision Generation for Human-human Augmentation. In *Proceedings of the 5th Augmented Human International Conference (AH '14)*. ACM, New York, NY, USA, Article 46, 8 pages. https://doi.org/10.1145/2582051.2582097

[20] Hiroki Kawasaki, Hiroyuki Iizuka, Shin Okamoto, Hideyuki Ando, and Taro Maeda. 2010. Collaboration and Skill Transmission by First-person Perspective View Sharing System. In *19th International Symposium in Robot and Human Interactive Communication*. 125–131. https://doi.org/10.1109/ROMAN.2010.5598668

[21] Christian Mai, Lukas Rambold, and Mohamed Khamis. 2017. TransparentHMD: Revealing the HMD User's Face to Bystanders. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia (MUM '17)*. ACM, New York, NY, USA, 515–520. https://doi.org/10.1145/3152832.3157813

[22] Tomislav Pejsa, Julian Kantor, Hrvoje Benko, Eyal Ofek, and Andrew Wilson. 2016. Room2Room: Enabling Life-Size Telepresence in a Projected Augmented Reality Environment. In *Proceedings of the 2016 Conference on Computer-Supported Cooperative Work & Social Computing (CSCW '16)*. ACM, New York, NY, USA, 1716–1725. https://doi.org/10.1145/2818048.2819965

[23] Ronald Poelman, Oytun Akman, Stephan Lukosch, and Pieter Jonker. 2012. As if Being There: Mediated Reality for Crime Scene Investigation. In *Proceedings of the 2012 Conference on Computer Supported Cooperative Work (CSCW '12)*. ACM, New York, NY, USA, 1267–1276. https://doi.org/10.1145/2145204.2145394

[24] Ramesh Raskar, Jeroen Van Baar, Paul Beardsley, Thomas Willwacher, Srinivas Rao, and Clifton Forlines. 2003. iLamps: Geometrically Aware and Self-configuring Projectors. *ACM Transaction on Graphics* 22, 3 (July 2003), 809–818. https://doi.org/10.1145/882262.882349

[25] Ramesh Raskar, Greg Welch, and Henry Fuchs. 1998. Spatially Augmented Reality. In *In First IEEE Workshop on Augmented Reality (IWAR '98)*. 11–20.

[26] Pejman Sajjadi, Edgar Omar Cebolledo Gutierrez, Sandra Trullemans, and Olga De Troyer. 2014. Maze Commander: A Collaborative Asynchronous Game Using the Oculus Rift & the Sifteo Cubes. In *Proceedings of the First ACM SIGCHI Annual Symposium on Computer-human Interaction in Play (CHI PLAY '14)*. ACM, New York, NY, USA, 227–236. https://doi.org/10.1145/2658537.2658690

[27] Unity. 2018. Chroma Key Kit - Asset Store. https://assetstore.unity.com/packages/tools/particles-effects/chroma-key-kit-71684 (accessed on 1 January 2019).

[28] Valve. 2016. Virtual Reality - SteamVR featuring the HTC Vive. https://www.youtube.com/watch?v=qYfNzhLXYGc (accessed on 1 January 2019).

[29] Andrew Wilson, Hrvoje Benko, Shahram Izadi, and Otmar Hilliges. 2012. Steerable Augmented Reality with the Beamatron. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST '12)*. ACM, New York, NY, USA, 413–422. https://doi.org/10.1145/2380116.2380169

[30] Yu Zhu, Kang Zhu, Qiang Fu, Xilin Chen, Huixing Gong, and Jingyi Yu. 2016. SAVE: Shared Augmented Virtual Environment for Real-time Mixed Reality Applications. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1 (VRCAI '16)*. ACM, New York, NY, USA, 13–21. https://doi.org/10.1145/3013971.3013979