How Display Shapes Affect 360-Degree Panoramic Video Communication

Leave Authors Anonymous
for Submission
City, Country
e-mail address

Leave Authors Anonymous
for Submission
City, Country
e-mail address

Leave Authors Anonymous
for Submission
City, Country
e-mail address

ABSTRACT

Field-of-view limitation has been a long standing issue in video communication systems. With the advancement of omnidirectional panoramic technology, the omnidirectional camera, which can provide a 360-degree field-of-view, has gotten more and more popular within the last few years. Previous research indicated that one-way video communication systems with a wider field-of-view improves task efficiency. Therefore, we propose to utilize omnidirectional cameras in a symmetrical video communication system and study how it affects remote collaboration. In this study, we conducted experiments with two conditions (omnidirectional camera + spherical display vs. omnidirectional camera + horizontally placed 2D flat display) and analyzed how the display types affected remote collaboration. Our results show that participants slightly preferred the spherical display than the 2D flat display. We also show the advantages and disadvantages of each display. The findings contribute to our understanding of how to design an environment for remote collaboration that captures and shows 360-degree panoramic view of a remote site.

ACM Classification Keywords

H.4.3 **Information Systems Applications**: Communications Applications – Computer conferencing, teleconferencing, and videoconferencing

H.5.3 **Information Interfaces and Presentation**: Group and Organization Interfaces – Collaborative computing, Computer-supported cooperative work, Evaluation/methodology, Synchronous interaction

Author Keywords

Remote collaboration, video communication, telepresence, spherical display, field-of-view, omnidirecional camera

INTRODUCTION

A long standing problem with video communication systems was the limitation of the field-of-view. Some early studies on video communication systems [5] [7] [8] pointed out that the

CHI'16, May 07–12, 2016, San Jose, CA, USA

ISBN 123-4567-24-567/08/06. . . $15.00

DOI: http://dx.doi.org/10.475/123_4

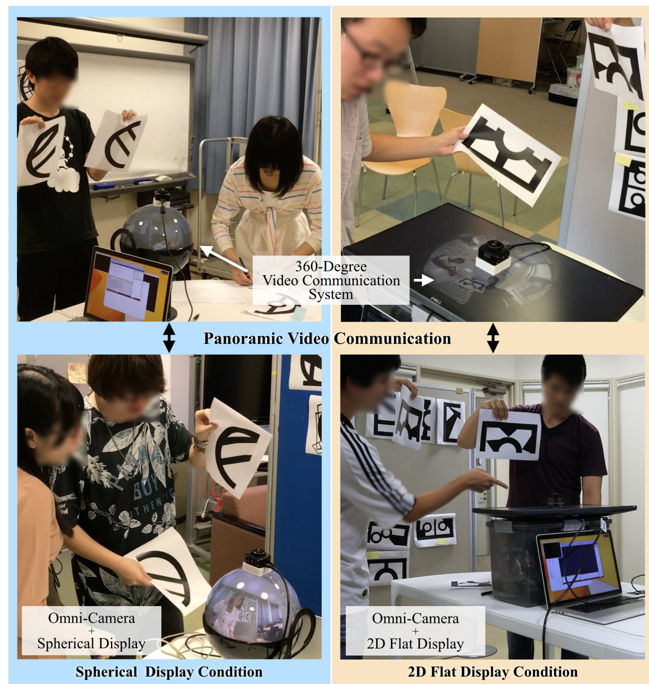

Figure 1: The 360-degree panoramic video communication systems. Two geographically separated rooms are connected by two different types of 360-degree panoramic video communication systems, a combination of omnidirectional camera and a spherical display (left column) or a horizontally placed 2D flat display (right column).

narrow field-of-view limits peripheral awareness of activities in a remote scene and often makes remote activities unnoticed. To solve this problem, Gaver et al. studied the effect of a system that virtually enhances the field-of-view by controlling a remote camera's movements using head movements in a local office. However, such mechanical solutions introduced some problems regarding system size, control speed, and accuracy.

Another possibility is to employ panoramic video technologies [14] [24] [31] which are widely available nowadays. Unlike traditional cameras, this new type of cameras can capture panoramic images in one shot which provides up to 360-degree field-of-view. Such technologies seem to open new possibilities to solve the problem of a narrow field-of-view. For example, Johnson et al.[14] compared remote operation of a telepresence robot using three kinds of field-of-view video feed:

narrow (45°), wide angle (180°), and panoramic (360°). Their results showed that wider views led to better task efficiency. However, the panoramic field-of-view increased complexity of the visual image and required greater cognitive load than a narrower field-of-view. Other studies like [16] and [31] affixed a 360-panoramic camera to a local participant so that a remote participant could view the captured images either by a head-mounted display (HMD) [16] or a tablet terminal [31] . Even with such solutions, however, remote participants seemed to have difficulty in perceiving spatial information of the local environment. Another issue of these studies is that, except for limited exceptions [21] [24] , proposed systems tend to create asymmetrical communication environment, i.e., system configurations are different between remote and local sites. It is pointed out that such asymmetricity of video communication environments disrupts reciprocity of communication [7] [20].

In this paper, we are interested in knowing whether these issue of increased complexity/workload and asymmetricity of communication could be improved by using a more proper camera-display configuration. We are particularly interested in understanding the pros and cons of using different types of displays in remote collaboration context that incorporates real-world objects. Although there are some display methods which can show 360-degree contents and also allow symmetrical video communication across distance, they have some issues when used for remote collaboration. For example, immersive projection technologies such as a panoramic dome display [1] or a cave display [10] confines users inside their space which limit user's interactions with real environment.

An alternative solution is to use a spherical display [2] [11]. Due to its three dimensionality, we can expect that a spherical display could naturally display the 360-degree images and reduce observers' cognitive load. Although conventional spherical display did not support symmetrical communication, Li et al.[17] proposed OmniEyeball as a new 360-degree panoramic video communication device that enables symmetrical communication. They embedded omnidirectional cameras into a spherical display system. The OmniEyeball can capture a 360-degree panoramic live video stream, send the data via wireless connection and also display the live video feed from another OmniEyeball on its spherical surface. Because the system can exchange the image of the whole environment around the devices, users are not constrained by the camera position or display orientation, i.e. users can position themselves anywhere around the device. Li et al. expected that the 360-degree panoramic video image using the OmniEyeball could improve telepresence of remote users and the performance of remote collaboration. However, they have not reported any user study with the system.

In our study, we compare two types of video displays (2D flat display vs. spherical display) for showing the 360-degree panoramic view of a remote site. We explore how the shape of the displays affects remote collaboration that incorporates real physical environment. The findings contribute to our understanding of how to design an environment for remote collaboration that captures and shows 360-degree panoramic view of a remote site.

RELATED WORK

Effect of Field-of-view in Video Communication

Problems caused by narrow field-of-view of a video camera has been discussed since the early studies of video communication systems [5] [6] [7] [15]. Fish et al. pointed out that reciprocity between participants such as "if you can see someone else, they can see you" [5] was not maintained in their VideoWindow system. For example, it was easy for a participant to stand outside of the field-of-view of a camera so that even though he/she could see remote participants, they could not see him/her. They further commented that they needed new ideas in design and placement of cameras and monitors. To challenge this issue, Gaver et al. proposed to use multiple cameras and monitors to cover a wider range in a collaboration space. However, they found that "the necessity of switching among views increased the difficulty of establishing the relations among them and negotiating a mutual orientation towards the task [7]."

In their subsequent study, Gaver et. al [8] tested the effect of a remote controlled camera which was expected to overcome the limitation of a narrow field-of-view. However, the system revealed various problems due to unavoidable features of mechanical systems in control, i.e., delay, accuracy, and noise. Then, as a future direction, they suggested to employ fisheye view image [9]. Recently, Luff et al. have conducted an experiment using multiple telepresence robots [29]. However, they also suffered from the narrow field-of-view problem and suggested to employ spherical images.

To investigate how the different field-of-view affect remote collaboration, Johnson et al. compared three field-of-view angles (narrow (45°), wide-angle (180°), and panoramic (360°)) of a camera on a telepresence robot [14]. Their experimental results indicated that wider field-of-view supported better task efficiency. However, they also pointed out that users felt more difficulty in perceiving panoramic view, suggesting the necessity for further exploration of user interfaces for a panoramic video communication system. Even though there are some other studies that explored the use of 360-degree panoramic video system [16] [31], another issue for these systems is that their system configurations were asymmetrical. In other words, users at a local site could see the 360-degree panoramic video that captured the remote site, but not vice versa - the video configuration did not allow equal contribution from both local and remote sites.

Meanwhile, some studies have already proposed video communication systems that enable the exchange of wide field-of-view images symmetrically. CamBlend [24] was a symmetrical video conferencing system that integrated wide field-of-view(180°) images with high-precision in-context views. However, this system could cover only one side of the room. t-Room [33] [32] is a room size video communication system that consists of multiple screens, cameras, and tables and enables to exchange panoramic images of the two rooms over the distance. The system creates an illusion of merging two geographically separate rooms. However, the actual shared area in the t-Room is constrained to the area close to the screen surfaces. Therefore, it is still challenging to realize a symmetrical video communication system that enables to exchange spherical images over the distance.

Spherical Image System

As suggested by Gaver et al. [9] and Liccope et al. [18], we are interested in using spherical images (360-degree panoramic images) for video communication. In this section, we briefly review the technologies related to spherical images. One of the recent trends in digital (video) cameras is the omnidirectional camera. Although the technology has been explored for a relatively long time, recent advancement in digital technology made high definition omnidirectional panoramic cameras affordable to general consumers.

Various display methods have been proposed to view such spherical images. One method is to simply use an ordinary 2D flat display. For example, the whole spherical image can be shown by distorting the image in a circular shape or, to reduce the distortion, by showing part of the image and allowing users to control the viewing orientation using cursor keys or a pointing device (QuickTime VR or Application of Ricoh Theta [1]). Instead of using an ordinary 2D flat display, there are some alternative methods. A recent trend is to use a HMD or to use a mobile terminal. Another advanced method is to use a spherical display. GEO-COSMOS [22] is the world's first full color spherical display. However, because its diameter is 6 meters and weighs 13 tons, it is not suitable for ordinary users. With the advance of projection technologies, however, several smaller spherical displays have been prototyped [2] [4] [23] [27] [28] [26] and are even commercially available now [13] [12] [30] [3].

To overcome the problem of a narrow camera field-of-view, we are interested in using spherical images for video communication. To the best of our knowledge, in spite of the availability of spherical cameras and displays, no studies have explored how such technologies can support symmetrical video communication. Especially, it is important to explore the usability issue. Therefore, this study compares two display methods for spherical images, 2D flat displays and spherical displays. We decided not to include VR HMDs or mobile terminals because such systems cannot show the whole spherical image at once and introduce the narrow field-of-view problem.

Collaboration with Symmetrical System Configuration

Many studies have been investigating how video communication technologies can support remote guidance, e.g., a remote helper gives instructions to a local worker to manipulate objects or showing physical locations in a local site [6] [20] [15]. Typically, these collaborations require referencing, showing, and manipulation of real world objects [18]. With only a few exceptions [21] [18], tasks for most of such studies are unidirectional, i.e., from a remote participant to a local participant, and the system configuration is asymmetrical between remote site and local site. Our current study, on the other hand, investigates systems that supports remote collaboration with symmetrical system configuration. For instance, participants conduct equally complex task on both geographically distributed sites while exchanging information to each other.

[1]https://theta360.com/en/about/application/

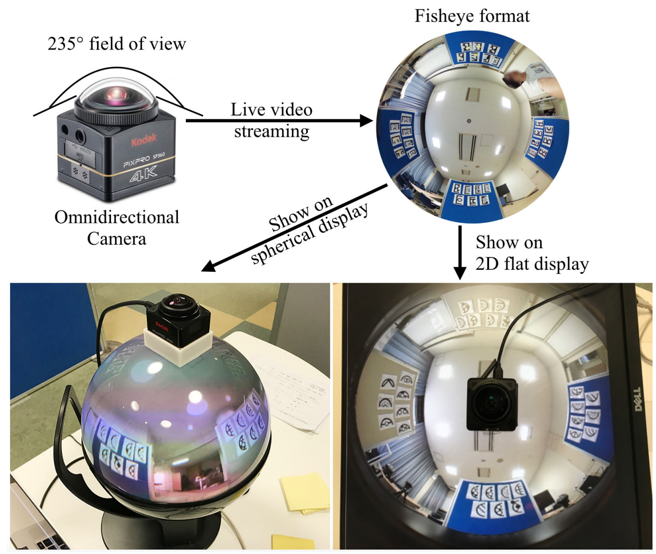

Figure 2: The diagram of the panoramic video system. The input of the system is from the Kodak camera. The output is either on the spherical display or the 2D flat display.

PANORAMIC VIDEO COMMUNICATION SYSTEMS

We configured a panoramic video terminal by integrating the omnidirectional camera with a display, which is either a hemispherical display or a 2D flat display. Hemispherical display type is identical to OmniEyeball. For this type, we integrated the WorldEye hemispherical display [3] with the Kodak PIXPRO SP360 4K camera [19] (Figure 2). The Kodak omnidirectional camera is attached atop the WorldEye display. The Kodak camera is equipped with a fisheye lens which covers a 235-degree field-of-view. It compresses the 235-degree space into a circular fisheye image by equidistant projection and the fisheye image can be easily shown in the WorldEye display. The WorldEye display is a hemispherical display with output resolution of 480*480. By feeding a circular hemispherical image to the WorldEye display, it can directly map the image onto its hemispherical screen. The Kodak camera is able to output a 1440*1440 pixels live video stream with 5fps over a USB connection. Then an image processing module on a PC receives the video stream, converts the resolution to 480*480 pixels, and sends it to the WorldEye display.

In this study, for panoramic video communication, we interconnected two identical panoramic video terminals in different rooms via LAN (local area network).To be more specific, live video stream captured by the local omnidirectional camera is transformed to 480*480 pixels, transferred to the remote counterpart terminal using TCP/IP protocol, and displayed on the remote hemispherical display. For audio transmission, we used Skype.

For the 2D flat display type, we employ DELL 24-inch display. To minimize the difference between the two types of displays, the PPI (pixel per inch) were set to be the same in order to achieve same display effect in both conditions. Otherwise, we employed the same technologies for video/audio transmission.

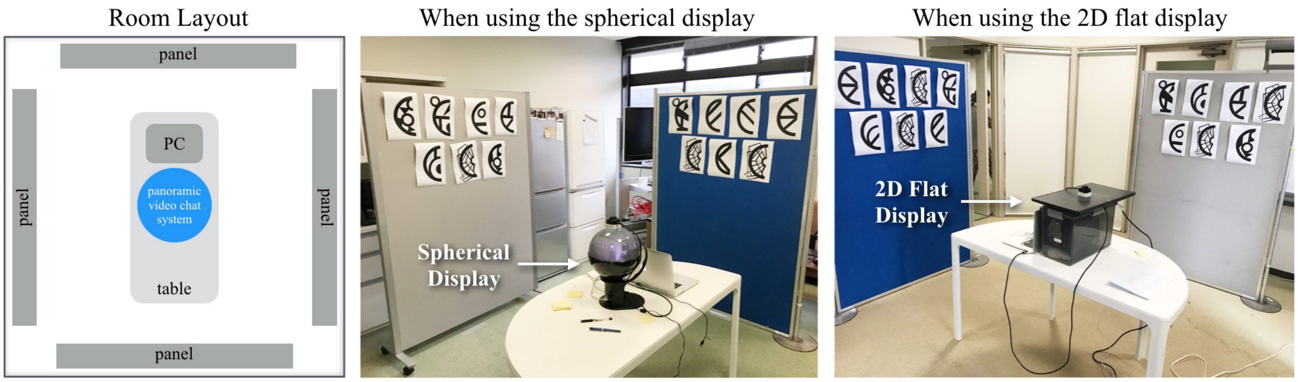

Figure 3: Left: The physical layout of both two rooms. Middle and Right: The real environment of the room when using the spherical display or the 2D flat display.

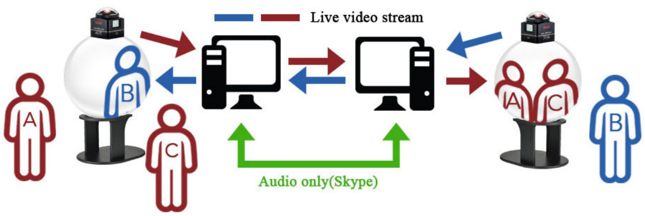

Figure 4: The diagram of the panoramic video communication system. Person B and C are standing across from each other.

This omnidirectional communication system requires careful directional calibration to enable one-to-one communication between two environments. For instance, as shown in Figure 4, the orientations of cameras and spherical displays should be properly configured in a way that if C stands across from B (in the display) in one end, also B should stand across from C in the other end.

EXPERIMENT

Using two types of symmetrical panoramic video communication systems, we conducted an experiment to explore the possibility of using omnidirectional cameras for remote collaboration. Especially, we are interested in the impact of display types on 360-degree panoramic video communication. Specifically, we plan to answer the following questions:

1. How do users perceive the video images differently between the 2D flat display and the spherical display?
2. How does the display type affect participants' actions during remote collaboration in a real physical environment?

Method

We based our research on four people remote collaboration because the panoramic video communication is able to support group-to-group remote communication. In order to study the features of a 360-degree field-of-view, we designed a pattern matching task which asked the participants to walk around the video communication system.

Conditions

We compared the 360-degree panoramic video communication between hemispherical camera + hemispherical display (spherical display condition) vs. hemispherical camera + horizontally placed 2D flat display (2D flat display condition)(Figure 1). For this experiment, we employed OmniEyeball technology (spherical display condition) because it has been the only existing system that enables asynchronous communication in a real physical environment. However, its apparent drawback is that one should walk around the terminal to observe the whole hemispherical image. Therefore, we also designed a system that employs a horizontally placed 2D flat display. Our intention is not to prove one is better than the other. Rather, we aim to investigate how the symmetrical video communication in a real physical environment can be supported by two possible technologies and figure out the pros and cons of each technology.

Apparatus

We used two mutually isolated rooms with the identical arrangement as communications sites (Figure 3). There were four panels (representing four walls) and one table in each room. The table was set in the middle and the distances between the table and four panels were the same. The two rooms were connected by panoramic video communication system using a gigabit network. The displays were located at the same height for both conditions.

Participants

Ten groups of four participants (40 people in total) were recruited for this experiment. The average age was 23.5 years old. 21 of them were students in the department of computer science. 29 people used video communication applications in their daily life. No participants had prior experience with panoramic video communication systems.

Task

Each task consists of four participants, with two participants collocated in one room. One room was provided with a set of 28 geometric pattern figures, each figure printed on a sheet of paper. These figures were put up on four panels (seven figures on each panel) in the room. The other room was given the same set of figures put up in different positions of the

Category	Question
Visual Cognition	Q1. It was easy to identify the objects/figures shown in the display.
Presence	Q2. I felt as if the remote participants were in the same room.
	Q3. I had a feeling of closeness to the remote participants.
Perceived Workload	Q4. I felt tired to work with the remote participants.
Communication Difficulty	Q5. I had difficulty in talking to only one of the two remote participants.

Figure 5: Five questions in the questionnaire designed on a five-point scale (1 = Strongly Disagree to 5 = Strongly Agree) to measure the feelings of participants after using panoramic video communication systems with two different displays.

Category	Question
Compatibility	Q6. For displaying 360 panoramic image, which type of display do you think is better?
	Q7. Which display is easier and faster for searching?

Figure 6: Two additional questions in the questionnaire to ask participants' preference between the two displays.

four panels. We asked the participants to match all the figures collaboratively across the rooms. Time was measured during the task and all participants were asked to finish the task as quickly and correctly as possible. If needed, they could take off the figures from the panels freely to show them to the remote partners or just to rearrange the figures. Scotch-tapes were used on the back of the figures so that they could easily put figures back to the panels.

Design of our collaborative task is affected by [24] [14] and [18] in that it requires participants to move around in a shared space, and show objects to remote participants, identify remote objects, refer to remote objects, and ask remote people to manipulate remote objects. Although it may not be naturalistic, we designed our task to incorporate as many of these actions as possible.

The experiment was within-participants design, i.e., participants conducted the task in two rounds, once in the spherical display condition and once in the 2D flat display condition. Therefore, two different sets of figures were prepared so the two rounds of tasks would not use the same figures. In addition, the two different sets of figures were used for the two conditions in alternation, thus the difference of difficulty between the two sets did not affect the results of the experiment.

Each group had to complete two rounds of tasks. Half of the groups used the spherical display in the 1st round and used the 2D flat display in the 2nd round, while the other half did it in the opposite order.

Procedure

1. Preparation: Firstly, participants were given a brief introduction to the experiment and panoramic video communication system, introduced to each other, split into two groups and did a practice round with six figures. After the practice, the correctness of their answers was checked and they were given two minutes to discuss how to complete the task more efficiently in the main experiment.

2. Main experiment: Five of the ten groups started the round with the panoramic video communication using the spherical display and the other five groups started using the 2D flat display. They were asked to match all the 28 different figures with the corresponding figures in the other room. Stickers and pens were prepared on the table so they could number the figures by writing the number on the sticker and stick it on the figure. When they finished all the figures for the first round, participants were asked to complete a short questionnaire concerning their thought about the condition in the first round. Then the display was replaced by the other one and the figures were also changed to the other set. Next, participants were asked to do the second round of task with the same rules. When they finished the task, participants completed another short questionnaire about the current condition.

3. Debriefing: After finishing the two rounds of task, participants filled in a final questionnaire about their opinions and comments on the two conditions and also the overall impressions about panoramic video communication.

Measures

We employed objective and subjective measures in order to examine task efficiency and users' perception of video images during the remote task. Each session was video-taped for post-analysis.

Objective Measures

We evaluated the collaborative efficiency based on completion time (the time it took the participants to complete the task) and completion accuracy (the number of correct pairs/total pairs).

Subjective Measures

We conducted a post-task questionnaire consisting of 5 questions per condition (10 in total), designed on a five-point scale (1 = Strongly Disagree to 5 = Strongly Agree) to measure the feelings of participants after using the panoramic video communication systems with two different displays. We expected that most of the variance in the answers of the questionnaire could be explained by four sets of correlated questions, which are "Visual Cognition", "Presence", "Perceived Workload" and "Communication Difficulty", respectively. The detailed questions are listed in Figure 5.

In addition, Compatibility – a measure of the participants' feeling regarding which display is more proper for the 360-degree video communication system, was evaluated by 2 question shown in Figure 6. The participants could answer them by choosing from "Spherical display", "2D flat display" or "Same".

The features including pros and cons of both displays were investigated by additional free-response question. Question contributing to this measure was: "*Please write down the advantages and disadvantages of each display which are found in this experiment*". The participants' qualitative comments for the free-response question were used to sum up the pros

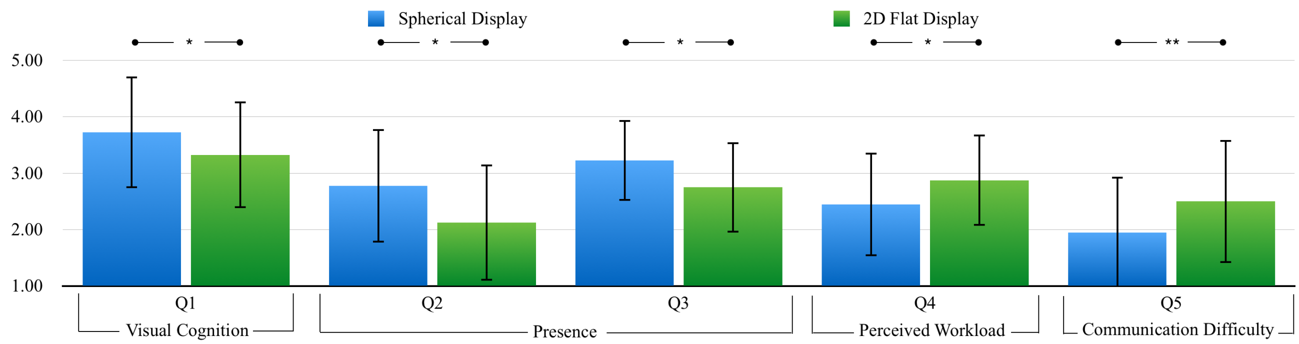

Figure 7: Mean scores of questions from Q1 to Q5. "*" and "**" denote significant difference at p < 0.05 level and < 0.01 level. The error bars depict the standard deviation.

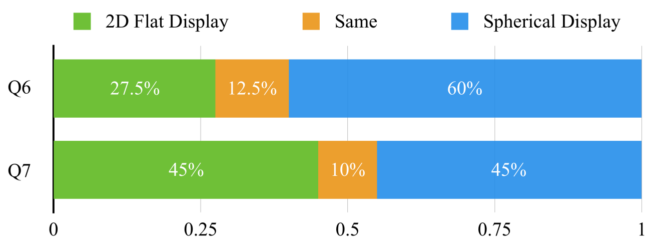

Figure 8: The statistical results of Q6 and Q7.

and cons of the two displays, which might also help to support the results of the above questions.

RESULTS

To answer to the research questions stated above, we conducted quantitative and qualitative analysis to the experiment data. Firstly, we analyzed collaboration efficiency and then analyzed the questionnaire results to see how the display types affect user perception. Finally, we analyzed participant comments and video recordings to see how display type affected remote collaboration.

Collaboration Efficiency

The average task completion times were 485.6 seconds (SD = 71.65) and 513.6 seconds (SD = 124.29), by using the spherical display and the 2D flat display, respectively. Wilcoxon signed-rank test showed no significant difference between the two conditions (Z = -.7139, p =.4752). As for the completion accuracy, the average task completion accuracies were .9892 (SD = .0339) and .9928 (SD = .0226), respectively. Wilcoxon signed-rank test showed no significant difference between the two conditions (Z = -.0743, p =.9407).

As for the results of the questionnaires, since Kolmogorov-Smirnov test showed significant difference between the distributions of the two sample sets, we ran a Wilcoxon matched pairs test.

Questionnaire Results

As shown in Figure 7, the results of the questionnaires were analyzed using Wilcoxon signed-rank test with the display condition as the factor.

1. Visual Cognition – The average scores of Q1 were 3.73 for the spherical display, 3.33 for the 2D flat display and we found a significant difference (Z = 2.0296, p = .0424) between the two conditions. According to the results, the participants seemed to feel that images in the spherical display were easier to recognize than the images shown in the 2D flat display.

2. Presence – The average scores of Q2 were 2.78 for the spherical display, 2.13 for the 2D flat display and there was a significant difference (Z = 2.5098, p = .0121). The average scores of Q3 were 3.23 for the spherical display, 2.75 for the 2D flat display and there was a significant difference (Z = 2.1059, p = .0352). Overall, it seems that the spherical display provided a stronger feeling of telepresence than the 2D flat display.

3. Perceived Workload – The average scores of Q4 were 3.73 for the spherical display, 3.33 for the 2D flat display and we found a significant difference (Z = -2.2141, p = .0268) between two conditions. The results indicate that the participants felt more fatigued when using the 2D flat display.

4. Communication Difficulty – The average scores of Q5 were 1.95 for the spherical display, 2.50 for the 2D flat display. We found a significant difference between two conditions (Z = -3.0918, p = .0019). The results indicate that the participants seemed to feel harder to have one-to-one conversation when using the 2D flat display than using the spherical display.

5. Compatibility – According to the results of Q6, 60 percent of the participants thought that the spherical display is better for displaying the 360-degree panoramic image. The results of Q7 indicate that the 2D flat display is equally fast and easy as the spherical display for searching in the display, shown in Figure 8.

Findings from Participants' Comments

Participants' comments were obtained from the free-response question in the questionnaire. Figure 9 summarizes the spherical display's advantages as well as disadvantages with the corresponding number of participants.

Opinions about the 2D flat display were also gained from the results of the free-response question. The advantages and

Advantages of the spherical display	Number of people
Strong three-dimensional sense	20
The spherical display is easier to be seen because of less distortion	20
The spherical display is more natural to be seen. Users just need to lower their head a little bit to see the display	10
Since the spherical display only shows half of the 360-degree images, it brings a better feeling of private conversation with remote partner and they would not be disturbed by the information from the opposite side	8
The spherical display provides better sense of position and directional relation	6
The sense of telepresence is better, which leads to a good feeling of conversation	6
The image on the spherical display is visible from anywhere in the room	5
Users can better be aware of the space range where the remote partner can see, which helps to understand what they are saying	3
Disadvantages of the spherical display	**Number of people**
Users often have to walk around to check the other sides of images, which is not convenient	30
Sometimes, users get lost with their remote partners or just hear the voice of remote partners without seeing them	5

Figure 9: The pros and cons of using the spherical display in the panoramic video communication.

Advantages of the 2D flat display	Number of people
Users can directly see the whole 360-degree image	32
They could put lots of objects above the omnidirectional camera to show them and they knew that these objects could be seen by the remote partners	3
Disadvantages of the 2D flat display	**Number of people**
The distortion is too serious to make it easy to be seen	23
It is hard to see the display clearly from a slight distance	9
Always have to lower head which is tiring	8
The sense of distance and space is bad	5
Sometime, it is hard to tell which remote partner is talking to you	4
Figures shown on the other side are inverted. If users want to see it clearly, walking is still needed	2

Figure 10: The pros and cons of using the 2D flat display in the panoramic video communication.

disadvantages of the 2D flat display are summarized in Figure 10 with the corresponding number of participants.

Findings from Observational Analysis

In addition, we found distinctive scenes in the video recordings of the experiment. For example, sometimes participants directly communicated when standing on different sides, which was not common in the experiment. Furthermore, participants seemed to have difficulties showing an object (i.e. sheet of paper with printed images) to remote partners in the 2D flat display condition due to camera occlusion.

Communication When Standing On Different/Opposite Sides

In the experiments, four participants always split into two groups for parallel working in order to increase the efficiency. Most of the time, participants stood across from their remote partner or at least on the same sides, which brings them a more natural feeling of communication. By standing across from each other, participants were not only visible to each other during the conversation in the spherical display condition, or in the 2D flat display condition but they could also avoid seeing an inverted figure or object. However, some distinctive scenes we observed were that participants communicated when standing on opposite sides, which means that person A in local room was standing on one side of the system, while person A's remote partner in remote room was standing on the opposite

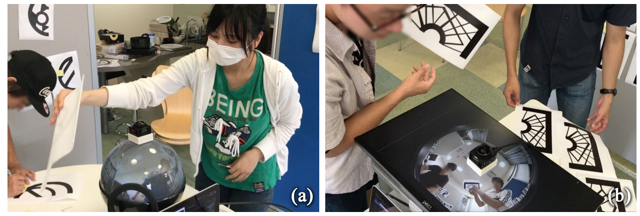

Figure 11: Communication when standing on opposite sides: The local participant directly put the image on the opposite side to show it to the invisible remote partner (a). By seeing the inverted image, the local participant directly talked to the remote partner who was standing in the opposite side (b).

side of the remote system. In the 2D flat display condition, it represents that the image of the remote partner was inverted from the local A's point of view. While in the spherical display condition, it means that the image of the remote partner was in the opposite side which was invisible to the local A. Three out of ten groups were found to do this type of communications (four times in total) in the spherical display condition. Since the remote partner was invisible, the conversation seemed to mainly rely on voice communication. As an extreme case, there was one occurrence of a participant directly showing an image to an invisible remote partner, as shown in Figure 11(a). On the other hand, this kind of conversations were observed more frequently in the 2D flat display condition (19 times in seven groups). As shown in Figure 11 (b), the person holding a figure was talking to the remote partner who was also holding a figure. Although the image of the remote partner was inverted from the local person's point of view, we believe that the 2D flat display made this type of conversation happen easier because the remote partner was visible. In addition, we observed that when such scenes happened in 2D condition, 4 participants usually paused the parallel one-to-one communications and communicated together.

Difficulties of Showing Objects with 2D flat Display

Another distinctive scenes were observed in the 2D flat display condition, which are that the participants met the camera occlusion issue when showing the figures to the remote partners. As shown in Figure 12(a)(b)(c), participants tried to put the figures on the exact top of the 2D flat display to show it. However, the image of the figure was blocked by the camera in the remote side because the Kodak camera captured the object on its top at the center of the image. Four out of ten groups were observed to suffer from this issue only when using the 2D flat display. Normally showing the image at the side of the 2D flat display could solve the occlusion issue. However, in the free-response question, two participants indicated that "*They had to look down to the 2D flat display, while showing the objects at the side of the display instead of above the display made them feel inconsistent*." In the spherical display condition, we did not find this situation and participants could naturally show figures, as shown in Figure 12(d). The occlusion issue of 2D flat display was caused by the unusual configuration of the 2D flat display's video system. If the omnidirectional camera becomes much smaller or users get more used to this system, it might not become a serious issue. However, as mentioned in the participants' comments, "*it is not intuitive to look down*

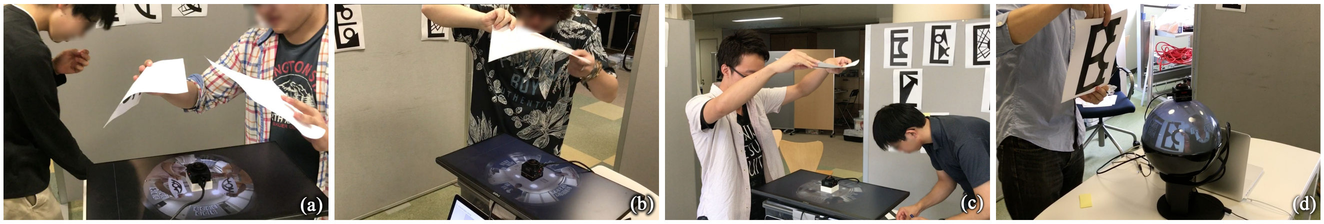

Figure 12: The camera occlusion issue was observed in the 2D flat display condition(a)(b)(c). While in the spherical display condition, we did not find this situation and participants could naturally show figures(d).

on the 2D flat display, while showing the objects at the side of the display."

DISCUSSION

The results of the objective measures, including completion time and accuracy, showed there was no significant difference of collaboration efficiency between the two conditions. Meanwhile, based on the questionnaire results, the results of 6 out of 7 questions showed that the spherical display was significantly better than the 2D flat display, indicating that the spherical display was slightly preferred over the 2D flat display as a whole. Below, we discuss the potential reasons for this result by focusing on other factors, e.g. visual perception, awareness, perceived workload and affordance.

Visual Perception, Awareness And Perceived Workload

We found that the 2D flat display enabled the participants to see everything in one view but increased their cognitive load due to image distortion and the necessity of mental rotation. The spherical display could only show half of the environment at once but provided a better visual cognition, sense of space and consistency/coherency of two distant spaces.

Such findings are supported by the questionnaire results and comments from the participants. The results of Q1 showed that the spherical display provided users a better visual cognition, which is supported by the participants' comments such as "*The spherical display has less distortion and stronger three-dimensional sense*" or "*The 2D flat display has severe distortion*". Besides the easiness to recognize the images displayed on the screen, participants also mentioned that "*The spherical display provides a better sense of space, distance and directional relation*" and "*The sense of distance and space is bad in 2D flat display condition*", which might explain the results of the questions related to presence (Q2 and Q3). Overall, these results indicate that the images displayed on the spherical display enabled the recognition of spatial relationships more intuitively and brought to a better feeling of telepresence. We suspect that such good sense of space, direction and telepresence helped to generate the consistency/coherency of two distant spaces.

On the other hand, the advantage of the 2D flat display was mainly reflected in the point that users could see the whole 360-degree images at a glance, which brings several merits. For instance, some participants mentioned that "*They could quickly locate remote partners or obvious objects by seeing the whole 360-degree image*."

However, seeing 360-degree images in one view might also bring problem to the 2D flat display. The results of Q4 indicated that the 2D flat display made users feel more fatigued. One explanation might be that 9 participants said "*They always have to lower head which is tiring when using the 2D flat display*". Another reason might be due to the overloaded visual information. Johnson et al. [14] indicated that 360-degree panoramic images were found to be more difficult to use than a 180-degree interface, which they believed supported the theory that wider field-of-view requires greater amounts of cognitive processing to synthesize the larger quantity of visual information provided. In our case, the reason why the participants thought that using the 2D flat display made them feel more fatigued may be because the 360-degree panoramic images include more visual information which adds to the cognitive processing burden. "*Sometime, it is hard to tell which remote partner is talking to you*", commented by four participants, was an issue caused by the overloaded visual information. Furthermore, two participants also mentioned that "*Figures shown on the other side are inverted. If users want to see it clearly, walking is still needed*". In fact, there were some instances that participants chose not to move around but observed the inverted figure which might have caused them mental rotation process. On the other hand, in the spherical display condition, participants did think that since the opposite side of the spherical display was invisible, they could see only the half of the 360-degree image. But some participants expressed that "*it provided them a more private conversation environment because they would not be distracted by the opposite half of the 360-degree image*", thus they could concentrate on the communication without distraction. In addition, 10 participants commented that "*The spherical display is natural to be seen, they just have to lower head a little bit to see the screen*". These factors might help the participants to lower the perceived workload when using the spherical display.

Moreover, we think that restricting the visual space (i.e. showing only half of the space) gives the spherical display more advantages in awareness of remote communication. Luff et. al [20] proposed an issue about the ecology of video communication. [20] noted that the local person may not be able to access where the remote person is looking at during the video communication, particularly when the field-of-view is wide. We found that the same issue happened in the symmetrical 360-degree video communication since the participants can see the whole remote space in 2D flat display condition. However, we infer that the issue may be resolved by using the spherical display. Indeed, three participants commented that

"*When using the spherical display, they can better be aware of the space range where the remote partner is able to see, which helps to understand what they are saying*." As an example, the girl in Figure 11(a) did not see her remote partner who was standing on the opposite side looking for her. However, she could directly show the image in the opposite side because she was aware of the space range where her remote partner was able to see. As for the 2D display condition, one participant wrote that "*he had no idea where the remote partner was looking at in the 2D flat display condition*".

Affordances of Displays

The scenes of the camera occlusion might indicate that the upward orientation of the 2D flat display affords participants to hold objects right above the display. The spherical display affords participants to naturally hold objects in front of their chest. The 2D flat display requires participants to look down to see the display which is quite unnatural for the participants when they are showing objects. A similar issue was also reported by Licoppe et al [18]. The spherical display does not have such issues.

In addition, we observed that participants in the 2D condition communicated slightly more as a group (with four people) than parallel one-to-one communication, compared with the spherical display condition. We suspect such findings might indicate that the spherical display better affords one to one conversation while the 2D flat display better affords many to many conversation. This point is also supported by 8 participants' comments, "*The spherical display brings a better feeling of private one-to-one conversation*". Moreover, the results of Q5 represented that it was easier to talk to a specific remote partner when using the spherical display.

Proper Real-World Scenarios

Comments about the 360-degree panoramic video communication were obtained from participants and they thought that "*The 360-degree video communication is not able to protect their privacy during video communication with families or friends in daily life, since the whole room is shown to the remote side*". But they did agree that "*The 360-degree field-of-view shows much more information than regular video communication and they felt better sense of the space, directional relation and telepresence of the remote side*." Participants indicated that "*The 360-degree video communication may be helpful in the video conference since there are multiple users in both sides to use the system*". We agree with this opinion and believe that the 360-degree video communication may also help to improve the collaborative efficiency of the remote collaboration tasks when users need to know a large amount of information about the remote side.

Based on the subjective results, the type of displays did not significantly change the collaborative efficiency. However, the questionnaire results showed that the spherical display was given a slight edge. Also, the participants felt that the images shown by the spherical display had less distortion, provided a better sense of space and direction. As a result, they appeared to perceive less workload when using the spherical display. Therefore, we propose the spherical display to be a more proper display for 360-degree video communication, particularly for group-to-group collaboration that requires showing and seeing real-world objects.

As a realistic scenario, recent discussion rooms tend to use a whole wall or multiple walls in a room as whiteboards, and a company like Smart Wall Paint [25] is proposing to transform any smooth surface in a room into a write-on wipe-off surface. With the advancement of video technologies, researchers have been envisioning to use the most of the surfaces in a room as video displays. In such a room, participants inevitably walk around in the room to use all the available surfaces, and refer to, manipulate, and discuss the objects/ drawings in the room. These trends increase the necessity for video communication systems to support collaboration between such rooms by solving the narrow field-of-view problem. We believe that remotely connecting such two discussion rooms through symmetrical 360-degree video communication may improve the remote communication efficiency.

LIMITATIONS AND FUTURE WORK

One of the limitations of our system was that we only supported hemispherical live video streams. We occasionally observed instances where a local participant exited the field-of-view of the camera when he/she bent down to put the image on the lower part of the wall. In such cases, a remote partner had to hold his/her talk and wait for the local participant to come back into the field-of-view. It is interesting to see that even hemispherical field-of-view was not wide enough to cover all the possibilities of the participants' bodies' spatial positions during the interaction. To solve this problem, we are currently developing a full-spherical version of the panoramic video communication system.

In addition, participants commented that they had to walk around to check the other side of the display in the spherical display condition. We think that a more proper solution is needed to allow users to see the other side of the spherical display instead of walking. The touch feature proposed by Benko et al. [2] could be taken into consideration.

CONCLUSION

This paper challenged one of the long standing issues of video communication systems, narrow camera field-of-view. We proposed two symmetrical 360-degree hemispherical video communication systems and explored their possibilities in assisting symmetrical remote collaboration. One of our interests were how the display shape, the 2D flat display or the spherical display, affects the remote collaboration. Our experimental results showed that both systems enabled multiple pairs of people to communicate over the distance simultaneously from anywhere around the devices. However, subjective results indicated that participants preferred the spherical display over the 2D flat display possibly due to better image quality (less distortion) and a better sense of three-dimensional space, directional relation and telepresence. Our future work includes extending our hemispherical system to full spherical system and better user interface for remote reference.

REFERENCES

1. Hrvoje Benko and Andrew D. Wilson. 2010. Multi-point Interactions with Immersive Omnidirectional Visualizations in a Dome. In *ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*. ACM, New York, NY, USA, 19–28. DOI: http://dx.doi.org/10.1145/1936652.1936657
2. Hrvoje Benko, Andrew D. Wilson, and Ravin Balakrishnan. 2008. Sphere: Multi-touch Interactions on a Spherical Display. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology (UIST '08)*. ACM, New York, NY, USA, 77–86. DOI:http://dx.doi.org/10.1145/1449715.1449729
3. Gakken Sta:Ful Co. 2013. WORLDEYE Spherical Display. (2013). http://www.gakkensf.co.jp/worldeye/
4. F. Ferreira, M. Cabral, O. Belloc, G. Miller, C. Kurashima, R. de Deus Lopes, I. Stavness, J. Anacleto, M. Zuffo, and S. Fels. 2014. Spheree: A 3D Perspective-corrected Interactive Spherical Scalable Display. In *ACM SIGGRAPH 2014 Posters (SIGGRAPH '14)*. ACM, New York, NY, USA, Article 86, 1 pages. DOI:http://dx.doi.org/10.1145/2614217.2630585
5. Robert S. Fish, Robert E. Kraut, and Barbara L. Chalfonte. 1990. The VideoWindow System in Informal Communication. In *Proceedings of the 1990 ACM Conference on Computer-supported Cooperative Work (CSCW '90)*. ACM, New York, NY, USA, 1–11. DOI: http://dx.doi.org/10.1145/99332.99335
6. Susan R. Fussell, Robert E. Kraut, and Jane Siegel. 2000. Coordination of Communication: Effects of Shared Visual Context on Collaborative Work. In *Proceedings of the 2000 ACM Conference on Computer Supported Cooperative Work (CSCW '00)*. ACM, New York, NY, USA, 21–30. DOI: http://dx.doi.org/10.1145/358916.358947
7. William W. Gaver. 1992. The Affordances of Media Spaces for Collaboration. In *Proceedings of the 1992 ACM Conference on Computer-supported Cooperative Work (CSCW '92)*. ACM, New York, NY, USA, 17–24. DOI:http://dx.doi.org/10.1145/143457.371596
8. William W. Gaver, Abigail Sellen, Christian Heath, and Paul Luff. 1993. One is Not Enough: Multiple Views in a Media Space. In *Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems (CHI '93)*. ACM, New York, NY, USA, 335–341. DOI:http://dx.doi.org/10.1145/169059.169268
9. William W. Gaver, Gerda Smets, and Kees Overbeeke. 1995. A Virtual Window on Media Space. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '95)*. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 257–264. DOI: http://dx.doi.org/10.1145/223904.223937
10. Markus Gross, Stephan Würmlin, Martin Naef, Edouard Lamboray, Christian Spagno, Andreas Kunz, Esther Koller-Meier, Tomas Svoboda, Luc Van Gool, Silke Lang, Kai Strehlke, Andrew Vande Moere, and Oliver Staadt. 2003. Blue-c: A Spatially Immersive Display and 3D Video Portal for Telepresence. *ACM Trans. Graph.* 22, 3 (July 2003), 819–827. DOI: http://dx.doi.org/10.1145/882262.882350
11. David Holman and Roel Vertegaal. 2008. Organic User Interfaces: Designing Computers in Any Way, Shape, or Form. *Commun. ACM* 51, 6 (June 2008), 48–55. DOI: http://dx.doi.org/10.1145/1349026.1349037
12. Global Imagination. 2008. Magic Planet spherical display. (2008). http://globalimagination.com
13. Pufferfish ltd. 2012. Puffersphere touch spherical display. (2012). https://pufferfishdisplays.com/solution/puffersphere-touch/
14. Steven Johnson, Irene Rae, Bilge Mutlu, and Leila Takayama. 2015. Can You See Me Now?: How Field of View Affects Collaboration in Robotic Telepresence. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2397–2406. DOI: http://dx.doi.org/10.1145/2702123.2702526
15. Brennan Jones, Anna Witcraft, Scott Bateman, Carman Neustaedter, and Anthony Tang. 2015. Mechanics of Camera Work in Mobile Video Collaboration. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 957–966. DOI: http://dx.doi.org/10.1145/2702123.2702345
16. Shunichi Kasahara and Jun Rekimoto. 2015. JackIn Head: Immersive Visual Telepresence System with Omnidirectional Wearable Camera for Remote Collaboration. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology (VRST '15)*. ACM, New York, NY, USA, 217–225. DOI: http://dx.doi.org/10.1145/2821592.2821608
17. Zhengqing Li, Shio Miyafuji, Toshiki Sato, and Hideki Koike. 2016. OmniEyeball: Spherical Display Embedded With Omnidirectional Camera Using Dynamic Spherical Mapping. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. ACM, New York, NY, USA, 193–194. DOI: http://dx.doi.org/10.1145/2984751.2984765
18. Christian Licoppe, Paul K. Luff, Christian Heath, Hideaki Kuzuoka, Naomi Yamashita, and Sylvaine Tuncer. 2017. Showing Objects: Holding and Manipulating Artefacts in Video-mediated Collaborative Settings. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 5295–5306. DOI: http://dx.doi.org/10.1145/3025453.3025848
19. JK Imaging Ltd. 2016. Kodak PIXPRO SP360 4K camera. (2016). https://kodakpixpro.com/Americas/cameras/vrcamera/sp3604k

20. Paul Luff, Christian Heath, Hideaki Kuzuoka, Jon Hindmarsh, Keiichi Yamazaki, and Shinya Oyama. 2003. Fractured Ecologies: Creating Environments for Collaboration. *Hum.-Comput. Interact.* 18, 1 (June 2003), 51–84. DOI: http://dx.doi.org/10.1207/S15327051HCI1812_3
21. Paul K. Luff, Naomi Yamashita, Hideaki Kuzuoka, and Christian Heath. 2015. Flexible Ecologies And Incongruent Locations. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 877–886. DOI: http://dx.doi.org/10.1145/2702123.2702286
22. Tamotsu Machida. 2002. GEO-COSMOS: World's First Spherical Display. In *ACM SIGGRAPH 2002 Conference Abstracts and Applications (SIGGRAPH '02)*. ACM, New York, NY, USA, 189–189. DOI: http://dx.doi.org/10.1145/1242073.1242202
23. Shio Miyafuji, Masato Sugasaki, and Hideki Koike. 2016. Ballumiere: Real-Time Tracking and Spherical Projection for High-Speed Moving Balls. In *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces (ISS '16)*. ACM, New York, NY, USA, 33–37. DOI: http://dx.doi.org/10.1145/2992154.2992181
24. James Norris, Holger M. Schnädelbach, and Paul K. Luff. 2013. Putting Things in Focus: Establishing Co-orientation Through Video in Context. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 1329–1338. DOI: http://dx.doi.org/10.1145/2470654.2466174
25. EXPRESS DECOR SP. Z O.O. 2016. Smart Wall Paint. (2016). http://www.smartwallpaint.com.pl/
26. Oyewole Oyekoya, William Steptoe, and Anthony Steed. 2012. SphereAvatar: A Situated Display to Represent a Remote Collaborator. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 2551–2560. DOI: http://dx.doi.org/10.1145/2207676.2208642
27. Ye Pan and Anthony Steed. 2012. Preserving gaze direction in teleconferencing using a camera array and a spherical display. In *3DTV-Conference: The True Vision-Capture, Transmission and Display of 3D Video (3DTV-CON), 2012*. IEEE, 1–4.
28. Ye Pan, William Steptoe, and Anthony Steed. 2014. Comparing Flat and Spherical Displays in a Trust Scenario in Avatar-mediated Interaction. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 1397–1406. DOI: http://dx.doi.org/10.1145/2556288.2557276
29. Revove Robotics. 2015. Kubi TelePresence Robot. (2015). https://www.revolverobotics.com/
30. LTD SHIBUYA OPTICAL CO. 2016. Glomal350 Ballscreen Projector. (2016). http://glomal.jp
31. Anthony Tang, Omid Fakourfar, Carman Neustaedter, and Scott Bateman. 2017. Collaboration with 360 Videochat: Challenges and Opportunities. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17)*. ACM, New York, NY, USA, 1327–1339. DOI: http://dx.doi.org/10.1145/3064663.3064707
32. Naomi Yamashita, Keiji Hirata, Shigemi Aoyagi, Hideaki Kuzuoka, and Yasunori Harada. 2008. Impact of Seating Positions on Group Video Communication. In *Proceedings of the 2008 ACM Conference on Computer Supported Cooperative Work (CSCW '08)*. ACM, New York, NY, USA, 177–186. DOI: http://dx.doi.org/10.1145/1460563.1460591
33. Naomi Yamashita, Katsuhiko Kaji, Hideaki Kuzuoka, and Keiji Hirata. 2011. Improving Visibility of Remote Gestures in Distributed Tabletop Collaboration. In *Proceedings of the ACM 2011 Conference on Computer Supported Cooperative Work (CSCW '11)*. ACM, New York, NY, USA, 95–104. DOI: http://dx.doi.org/10.1145/1958824.1958839