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Analysis of Depth Perception with Virtual Mask in Stereoscopic AR

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Abstract

A practical application of Augmented Reality (AR) is see-through vision, a technique that enables a user to observe an inner object located behind a real object by superimposing the virtually visualized inner object onto the real object surface (for example, pipes and cables behind a wall or under a floor). A challenge in such applications is to provide proper depth perception when an inner virtual object image is overlaid on a real object. To improve depth perception in stereoscopic AR, we propose a method that overlays a random-dot mask on the real object surface. This method conveys to the observers the illusion of observing the virtual object through many small holes. We named this perception "stereoscopic pseudo-transparency." Our experiments investigated (1) the effectiveness of the proposed method in improving the depth perception between the real object surface and the virtual object compared to existing methods, and (2) whether the proposed method can be used in an actual AR environment.

Categories and Subject Descriptors (according to ACM CCS): H.1.2 User/Machine Systems: Human factors; H.5.1 Multimedia Information Systems: Artificial, augmented, and virtual realities.

1. Introduction

A practical application of Augmented Reality (AR) is see-through vision, a technique that enables a user to observe a virtual object located behind a real object by superimposing the virtually visualized inner object onto the real object surface. This technique is considered to be effective in several areas, including medical [BWH*07][EJH*04][LCM*07][NSM*11][SBH*06] and industrial visualizations [SMK*09][ZKM*10]. In these applications, one challenge is determining how to cause a virtual object to appear behind a real object surface.

When using video-based stereoscopic displays, if an image of the inner object is simply overlaid onto the real object, a conflict occurs. In Figure 1 (a), for example, the binocular disparity depth cue correctly conveys to the observer that the virtual object (the light blue sphere) is farther away than the real object surface. The occlusion depth cue, on the other hand, implies that the virtual object surface must be closer than the intervening real surface, due to the fact that all pixels of the virtual object completely occlude the real surface. This conflict can obscure the spatial relationship for the observer, i.e., the anteroposterior relationship between the virtual object and the real object surface and the distance between them [KSF10][SJK*07].

To alleviate this problem, we proposed a method to overlay a virtual random-dot mask on the surface of a real object in a stereoscopic AR environment (Figure 1 (b)) [OM13]. This method conveys to observers the illusion of observing the virtual object through many small holes (Figure 2). We named this effect "stereoscopic pseudo-transparency" (we further discuss these terms in Section 2).

In this study, we investigate whether the proposed method actually improves the *transparency* and *depth* perception. In this paper, the *depth perception* implies not

(a) Overlaying the inner virtual object (light blue sphere) onto the real object.

(b) Using random-dot mask

Figure 1: *Examples of occlusion cue conflict (a) and of "stereoscopic pseudo-transparency" (b). (See section 3.1 for explanation.) Stereo pair AR images (cross-eyed stereo).*

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only the perception of the relative anteroposterior relationship between the real object surface and the inner virtual object, but also perception of the absolute distance between them.

In the rest of this paper, we first introduce the related work and describe the differences with our method. Next, in Section 3, using a simulated AR environment, we investigate whether the proposed method actually improves the *transparency*, and *distance perception* between the real object surface and the virtual object surface compared to existing methods. In Section 4, we investigate whether the proposed method can be used in an actual AR environment. In section 5, we discuss the result of the experiment and its limitations. Finally, we summarize our results.

2. Related Work

To improve observers' depth perception in AR, researchers have proposed several techniques. One of the popular methods is to create a virtual window (cutaway) on the real object surface and display only the inner object through this window [FAD02][SMK*09][SBH*06]. Livingston utilized mobile AR in an urban environment and also conducted a user study to determine which drawing style and opacity settings best express occlusion relationships among far-field objects [LSG*03]. Bichlmeier et al. modified the real surface to be semi-transparent and then visualized the virtual object as though the observer viewed it through the semi-transparent area [BWH*07]. Although researchers have partially confirmed that some of these techniques improved perception of the anteroposterior relationship of the real object surface and the virtual object, their effect on distance perception between them was not investigated.

Other researchers have proposed, in addition to making the real object surface semi-transparent, enhancing the texture of the surface by overlaying the surface image immediately above the virtual object image [APT07] [LCM*07][KMS07]. By enabling an immediate comparison between the surface texture and the virtual object, they showed that the observers' perception of the anteroposterior relationship between them was improved. However, these techniques cannot be applied when the real object surface does not have sufficient features to be enhanced, e.g., smooth human skin or large, flat walls.

Alternatively, we propose using a random dot mask as an add-on surface feature. We expect the mask can provide a depth cue even when there is no feature on the original object surface. We focus on two well-known phenomena, pseudo-transparency and stereo-transparency.

Pseudo-transparency is the effect that an intervening (real object) surface appears to be semi-transparent, similar to light passing through gaps in non-transparent lacy objects, such as wire fences or tree branches [TAW08] [TWA10]. *Stereo-transparency* is based on the power of stereopsis to overcome cues provided by intervening surfaces [AT88]. When users observe random-dot stereograms, they perceive the overlapping surfaces simultaneously at different depths in the same visual direction, and they perceive the front layer as transparent against more distant layers.

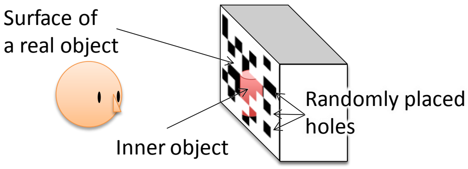


Figure 2: *The illusion of observing the virtual object through many small holes.*

Our proposed method of "*stereoscopic pseudo-transparency*" is based on these effects. As mentioned in Section 1, this method conveys the impression of observing a virtual object through many small holes (Figure 2). We predict that this illusion will induce the pseudo-transparency effect, and thus observers will perceive the front surface as transparent. In addition, we also predict that our random-dot mask will improve the perception of the overlapping real object surface and the virtual object simultaneously at different depths.

By using a random-dot mask, it is possible to apply our method to various surfaces regardless of the existence of surface textures. Another important advantage of this method is that it allows the observer to perceive the shape and colours of the original surface, which is difficult for traditional methods that make a virtual window on a real object surface [FAD02][SMK*09][SBH*06].

Zollmann et al. [ZKM*10] and Mendez et al. [MD09] proposed adding an artificial texture or a mask to a flat surface for such cases; however, they did not evaluate the effect of their technique on depth perception.

In this study, through the two experiments, we investigate whether our method improves depth perception, especially perception of the distance between the real object surface and the inner virtual object. We also examine the effectiveness of our proposed method in an actual AR environment.

3. Experiment 1: Effectiveness of Proposed Method for Transparency and Depth Perception

3.1 Objectives and Hypotheses

In this experiment we investigated whether our method improves depth perception relative to existing methods. Our hypotheses are as follows:

H1: Adding a random-dot mask on a real object surface without distinct texture will improve performance in perceiving the presence of the real object surface.
H2: Adding a random-dot mask enhances perception of whether the virtual object is behind or in front of the real object surface.
H3: Adding a random-dot mask improves perception of distances between the real object surface and the virtual object.

This experiment consists of two parts: experiment 1-1 to test H1 and H2, and experiment 1-2 to test H3. In these experiments, we compared our random-dot mask with other mask types which represent the methods proposed in the previous studies.

3.2 Image Generation and Presentation

In this experiment, all stimuli were generated on a desktop computer (Windows 7 Professional OS with NVIDIA Quadro 600), coded using Visual C++ 2010 and OpenGL, and presented on a 24-inch LCD screen (BenQ XL2420T, 1920×1080, 120 Hz refresh rate) with a black background. Stereo images were observed using the NVIDIA 3D vision system with 3D Vision 2 glasses. Participants used a chin rest placed 50 cm from the display to match the virtual eye position and convergence point in the program. (The setup was the same for experiments 1-1 and 1-2).

Figure 4 shows an example of a stimulus shown to participants. We put the mask at the same depth as the display surface and designated it the "masking area." The masking area was 184 × 184 px and the entire stimulus area was the full screen (1920 × 1080 px).

We designed the stimuli with a medical application in mind: the pink coloured surface represents the skin and the blue circle represents a possible blood vessel. We maintained the surface at a constant distance, corresponding to zero disparity for the stereoscopic display. The blue virtual circle's depth position could be located at varying distances in front of (closer to the participant) or behind the surface. To prevent participants from using the circle size as a cue, the size was kept constant regardless of the distance from the surface.

Many AR techniques overlay a virtual object onto the *real* object surface; however, in experiments 1 and 2-1, we employed a *simulated* real surface instead of a real one because we tried to eliminate such unpleasant factors as low-quality cameras. A similar technique was also employed by Ragan et al. [RWB*09].

3.3 Mask types

In the following *dot size* refers to the fraction into which each dimension is divided. For example, 1/10 means that a 10 × 10 grid was used to generate the random-dot pattern. Dot density refers to the percentage of the entire masking area that consists of dots. Note that dot size and density are independent of each other.

Figure 3 shows the masks used in this experiment:

(a) Without mask (simple AR): We ignored any depth relationship between the circle and the surface, such that the circle pixels always occluded all elements of the surface, regardless of whether it was drawn in front of or behind the surface.

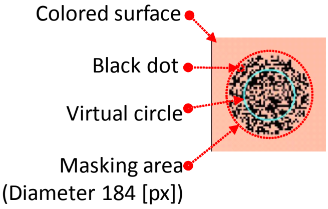


Figure 4: *An example of a stimulus (part).*

(b) Random dot (proposed method 1): By occluding the black dots with the virtual object, while occluding the virtual object by the non-dot pixels, observers could only partially see the virtual object behind the surface, through the black dots. We used a random-dot mask with a dot size of 1/60 of the mask area and dot density 50%. These values were based on the results of our previous study [OM13], in which we tested various densities and dot sizes to find the mask design that produced the best depth and transparency perception.

(c) Cut-away: Observers could see the entire circle within a large black circular area that was cut out of the surface. This mask type corresponds to related work in references [FAD02][SMK*09][SBH*06].

(d) Semi-transparent: This mask comprised a continuous black area with 50% transparency rendered by alpha blending. (This is a typical method for observing a virtual object occluded by a real object [FAD02].)

(e) Semi-transparent random-dot mask (proposed method 2): This is a combination of mask types (b) and (d), i.e., overlaying a 75% transparent random-dot mask (with dot size 1/60 and dot density 50%) over a 25% transparent semi-transparent mask. The intention here was to maintain the entire image of the virtual object, which would otherwise be partially removed with method (b).

3.4 Participants

15 students and faculty members at the University of Tsukuba (14 male, 1 female) aged between 22 and 38 participated in this study. All claimed to have normal or corrected-to-normal visual acuity and to be without stereoscopic vision problems. To confirm the latter, the NVIDIA 3D stereo vision test was administered.

3.5 Experiment 1-1: Investigation of H1 and H2

3.5.1 Objectives and Procedure

In all cases, the virtual circle was placed behind the

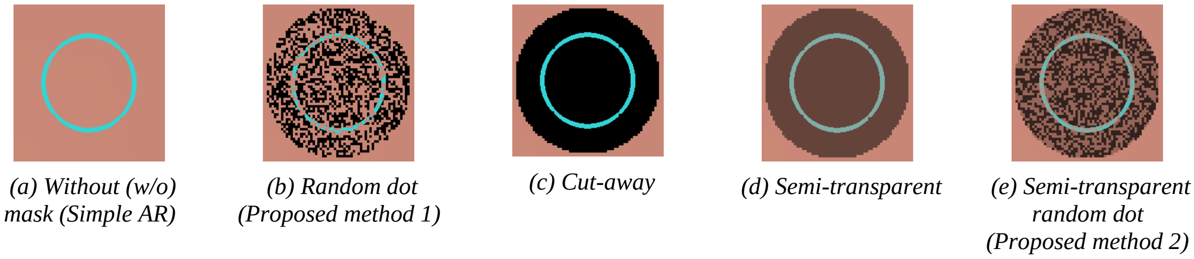
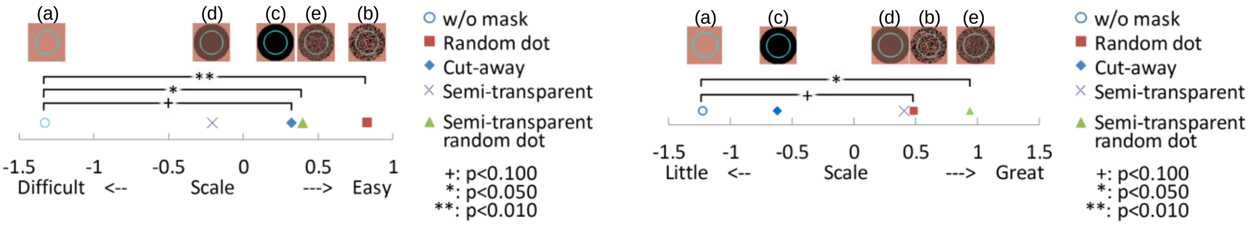

(a) Without (w/o) mask (Simple AR)
(b) Random dot (Proposed method 1)
(c) Cut-away
(d) Semi-transparent
(e) Semi-transparent random dot (Proposed method 2)

Figure 3: *Mask types in experiment 1.*



(a) Q1 "In which image is it easier to perceive that a circle is behind the surface?

(b) Q2 "Which image provides a greater impression of seeing a circle through the surface?

Figure 5: *Results of experiment 1-1.*

surface at a constant distance of –0.02 m. This distance was determined based on pilot tests. We explained this setting to all the participants..

To test H1 and H2, we used Thurstone's paired comparison scaling method [Thu27]. The participants observed pairs of stimuli and answered two questions (translated from Japanese):

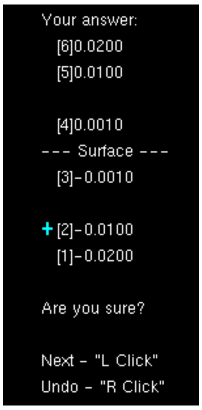
1. In which image is it easier to perceive that a circle is *behind* the surface?
2. Which image provides a greater impression of seeing a circle *through* the surface?

These questions verified that the participants were able to perceive that a virtual object was behind the surface. The second question explicitly queried whether they were conscious of the existence of the surface above the virtual object. Each participant compared ten ($_5C_2$) pairs twice, or 20 samples in total.

3.5.2 Results

Figure 5 presents the results of experiment 1-1. The horizontal axis indicates the rating scale values, where larger values signify more agreement for the corresponding parameter.

A Tukey's honestly significant difference (HSD) post-hoc test revealed that for Q1, random-dot mask and semi-transparent random-dot mask were significantly easier than w/o mask (simple AR) (p<0.01, and p<0.05, respectively). The difference between cut-away and w/o mask was marginally significant (p<0.1).


Your answer:
[6]0.0200
[5]0.0100

[4]0.0010
--- Surface ---
[3]-0.0010

+[2]-0.0100
[1]-0.0200

Are you sure?

Next - "L Click"
Undo - "R Click"

Figure 6: *Example of response menu for Experiment 1-2. The participants could select their answer by using the mouse wheel. The blue cross shows the current selected answer.*

Conversely for Q2, semi-transparent random-dot mask was significantly greater than w/o mask. The difference between random-dot mask and w/o mask was marginally significant. Although semi-transparent mask also seemed to achieve a greater score than the cut-away and w/o mask conditions, there was no significant difference. Some participants commented that semi-transparent mask did not markedly assist them in determining whether the circle was behind or in front of the mask.

These results support hypotheses H1 and H2.

3.6 Experiment 1-2: Investigation Regarding H3

3.6.1 Objectives and Procedure

To test hypothesis H3, we investigated the effect of distance on the perception between the surface and virtual object. We randomly presented the virtual circle at six different distances from the surface: three behind the surface {–0.02, –0.01, –0.001} m and three in front of the surface {+0.02, +0.01, +0.001} m. These distances were chosen on the basis of pilot tests. The distances of +/–0.001 were in close proximity to the surface, making them very difficult to distinguish.

Participants were requested to identify the distances by using a mouse wheel to select their answers from six distances shown in a menu, as shown in Figure 6. Each participant viewed 90 trials, representing 5 types of masks × 6 distances × 3 repetitions of each combination of masks and distances.

3.6.2 Results and Discussion

We focused on the difference in the correct answer rate between the mask types at each distance (Figure 7). A two-way factorial repeated-measures ANOVA indicated a significant main effect for both mask type (F(4,56)=41.741, p<0.001) and virtual object distance (F(5,70)=3.397, p<0.01). Their interaction was also significant (F(20, 280)=6.083, p<0.001).

The separate t-tests with Bonferroni Correction confirmed that there were significant differences between w/o mask and all other mask types (p<0.05) in ±0.01 m and ±0.02 m. In –0.001 m, we also found significant differences between w/o mask and the other masks except for cut-away, and between cut-away and both random-dot mask and semi-transparent random-dot mask (p<0.05). In

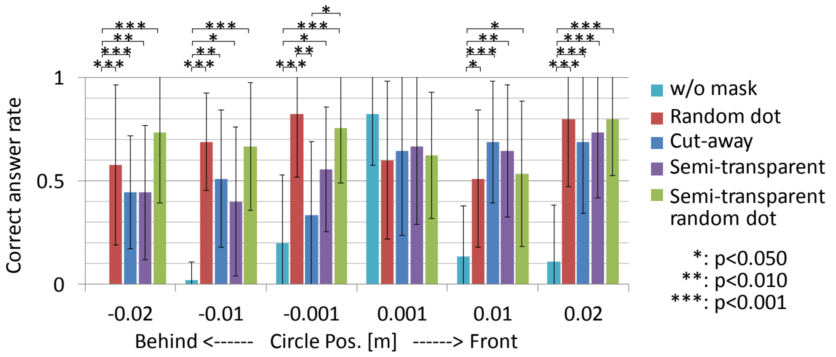


Figure 7: *Results of experiment 1-2. Correct answer rate of each mask type at each distance. Error bars represent standard deviation.*

+0.001 m, there was no significant difference. From these results, at least for ±0.01 m and ±0.02 m, the participants could distinguish the distances more correctly when masks were used compared to the w/o mask case.

When the circle was placed at the posterior vicinity of the surface (–0.001 m), the participants could distinguish the distance more correctly when the random-dot mask or semi-transparent random-dot mask was used compared to both w/o mask and cut-away. Overall, these results support hypothesis 3: random-dot masks improve perception of the distance between real object surfaces and virtual objects.

Note that the correct answer rate for +0.001 shows a different trend from other circle positions. When w/o mask was used, it was difficult for the participants to determine whether the virtual circle was behind or in front of the surface. Interestingly, in such cases, they tended to answer that the circle was +0.001 m (front vicinity of the surface) regardless of where it was placed. Consequently, the correct answer rate of w/o mask for +0.001 m is quite high. In the case of cut-away and semi-transparent mask, we assume that the lack of immediate reference between the surface and virtual object made it difficult for the participants to perceive the distance correctly.

4. Experiment 2: Effect of the Proposed Method in Actual AR Environment

4.1 Objectives

Experiments 1 indicated that the proposed method is effective in enhancing the perception of both the real object surface and the virtual object, and thus improved the distance perception between them in a stable environment. However, two limitations of the experiment were: (1) we eliminated any potential motion cues, which are known to be an important factor that improves depth perception in AR [FAD02], and (2) we used a simulated real surface instead of an actual real object surface. Therefore, to investigate both motion cues and more realistic situations, we designed experiment 2.

Experiment 2-1 retained a simulated real object but investigated whether our proposed method still has a significant effect in improving depth perception when combined with a motion cue. Experiment 2-2 was designed to test the effectiveness of the proposed method using an actual real object surface instead of a simulated real object surface, and a 3D virtual object instead of wireframe circle, while also allowing motion cues.

4.2 Experiment 2-1: Effect of Proposed Method When Used with Motion Cue

4.2.1 Image Generation and Presentation

In this experiment, all stimuli were generated on a desktop computer (Windows 8.1 OS with NVIDIA GeForce GTX650), coded using Visual C++ 2010 and OpenGL, and presented on a head-mounted display (HMD) (Oculus Rift DK2: Oculus Inc., 1920 x 1080 px resolution, 960 x 1080 px per eye), operating in stereoscopic mode. To provide motion cues, we tracked the position and orientation of the participant's head using the Oculus DK2's infrared-based tracker..

As in experiment 1, we simulated a skin-coloured real object surface and used a blue circle as the virtual object. The circles were positioned at various distances in front of and behind the surface.

4.2.2 Procedure and Participants

The procedure was similar to experiment 1-2. We randomly presented the virtual circle at six different distances from the surface: three behind the surface {–0.02, –0.01, –0.001} m and three in front {+0.02, +0.01, +0.001} m. The participants were requested to identify the distances between the real object surface and the virtual object the same way as in experiment 1-2. Each participant viewed 72 trials (2 mask conditions (with and without mask) × 2 motion cue conditions (with and without motion cue) × 6 distances × 3 repetitions).

In the with mask case, we used the same random-dot mask as experiment 1 (Figure 3 (b)). In the case with motion cue, we explained to the participants that they could move their heads freely as long as they were sitting on the chair. In the without motion cue case, the viewing point did not change even when they moved their heads.

13 students and faculty members at the University of Tsukuba, all male, aged between 22 and 31, participated in this study. All claimed to have normal or corrected-to-normal visual acuity without stereoscopic vision problems,

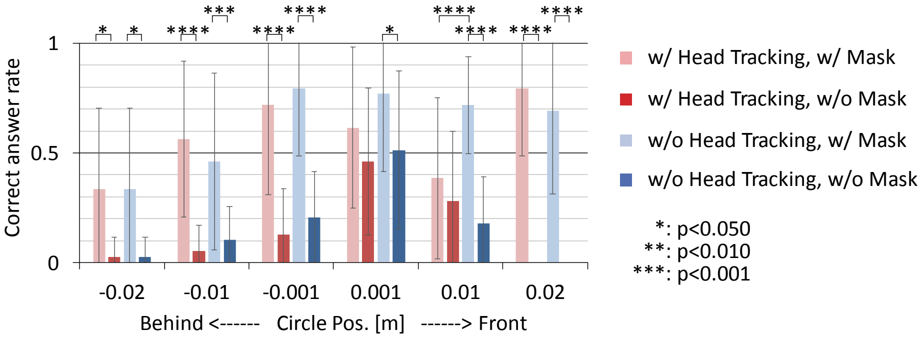


Figure 8: *Results of experiment 2-1. Correct answer rate of each mask and motion cue conditions and distance. Error bars represent standard deviation.*

which we confirmed by conducting the same vision test as in experiments 1.

4.2.3 Results and Discussion

Figure 8 presents the correct answer rate of each mask and motion cue conditions and distance. A three-way factorial repeated-measures ANOVA indicated that there was a statistically significant three-way interaction between mask conditions, motion cue conditions, and distances (F(5, 60) = 2.437, $p<0.01$). A simple two-way interactions test indicated a simple two-way interaction between distance and motion cues in the case without mask (F(5, 120)=3.255, $p<0.05$), between distances and mask conditions in the case without motion cue (F(5,120)=5.117, $p<0.001$), and between motion cue and mask conditions when the distance was −0.01 (F(1,72)=10.291, $p<0.01$). We also tested simple-simple main effects.

From these results, the correct answer rate of w/ mask was significantly higher than that of w/o mask at ±0.02, −0.01, and −0.001, regardless of the motion cue conditions. In addition, the correct answer rate of w/ mask was significantly higher at +0.01 and +0.001 in the case without motion cue. These results supported the hypothesis that the proposed method improved depth perception, particularly when the circle was behind the surface, even when the motion cue was available. There was also support for the hypothesis that the proposed method would improve depth perception compared to the without mask case, regardless of availability of the motion cue.

As mentioned above, no significant main effect was observed for the motion cue factor. We assumed that the motion cue was not very effective in our experiment, because the distance from the surface to the virtual object (2 cm maximum) was much shorter than the distance from the participant's head to the surface (around 50 cm).

4.3 Experiment 2-2: Effect of Proposed Method in Actual AR Environment

4.3.1 Image Generation and Presentation

In this experiment, all stimuli were generated and presented using the same PC and HMD as in experiment 2-1. For the head tracking, we used ARToolKit [KB99]. An important difference this time was that we created a video see-through augmented reality display, using an actual cork board as the real object surface and a stereo USB camera (Ovrvision, 640 x 480 px for each eye) to obtain the actual scene.

For the virtual stimulus, we used a blue sphere (0.02 m diameter), and placed it in front of or behind the cork board at 0.15 m to the left of a 2-D marker (0.05 m square). The experimental setup is shown in Figure 9. At the onset of the experiment, the participants were requested to adjust the height and position of their chairs to see the virtual sphere directly in front of them.

4.3.2 Procedure and Participants

Similar to experiments 1-2, we randomly presented the virtual circle at six different distances from the cork board surface: three distances behind the surface {−0.03, −0.02, −0.01} m and three distances in front of the surface {+0.03, +0.02, +0.01} m. As in experiment 2, participants were requested to identify the distances. Two mask conditions were used: with mask (as in Figure 10 (a)) and without mask (as in Figure 10 (b)). Each participant viewed 36 trials (2 with and without the mask × 6 distances × 3 repetitions). The observers' view of each mask condition is shown in Figure 10. We allowed the participants to move their heads freely, as long as they were sitting on the chair. (No without motion condition was included here.)

Ten students at the University of Tsukuba, all male and aged between 22 and 28, participated. All claimed to have normal or corrected-to-normal visual acuity without stereoscopic vision problems, which we confirmed by conducting the same vision test as in experiments 1.

4.3.3 Results and Discussion

Figure 11 shows the results of two mask conditions for

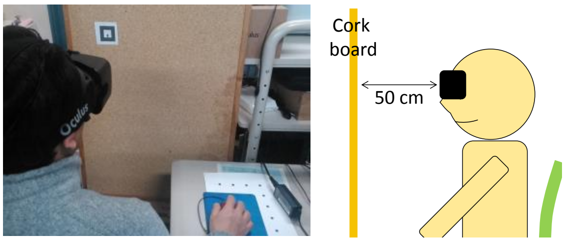


Figure 9: *Experimental setup in experiment 2-2. Marker on upper left part of cork board was for AR head tracking.*

each distance. A two-way factorial repeated-measures ANOVA indicated a significant main effect for both mask condition (F(1,9)=25.11, p<0.001) and virtual object distance (F(5,45)= 4.17, p<0.005). No significant interaction was found (F(5,45)=2.15, p=0.077).

These results supported the hypothesis that our proposed method also improves a user's depth perception, also in an actual AR environment.

5. Discussion

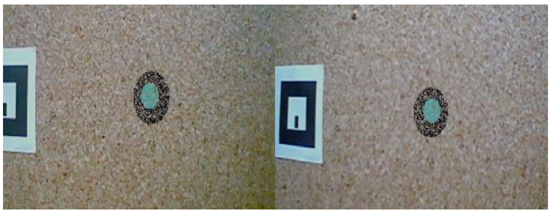
In this paper, to improve depth perception in stereoscopic AR, we proposed a method that overlays a random-dot mask on a real object surface. Our experiments supported our assertion that our proposed "stereoscopic pseudo-transparency" method has the potential to improve depth perception in stereoscopic AR. However, there are some limitations.

First, we need to further investigate the visibility of inner virtual objects. Because users observe virtual objects through many small holes, visibility of the virtual object is lower than in the case with a cut-away or the case without mask. For our future work, it is necessary to reconsider the appropriate transparency, dot density, and dot size for the random-dot mask from the aspect of visibility of the virtual object.

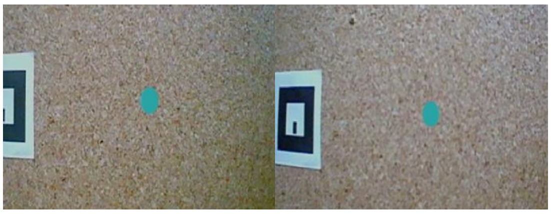
Another limitation is that our experiments were limited circumstances in terms of shapes, colours and textures, as well as complexity of the virtual objects and the real object surfaces. As mentioned in 3.2, we used a circular ring as the virtual object by considering a medical application. However, we still need to investigate whether our method is effective for various combinations of virtual objects and real object surfaces that have different shapes, colours, textures, and complexities.

As mentioned in section 2, our method allows the observer to perceive the shape and colours of the original surface, which is difficult for traditional methods that make a virtual window on a real object surface [FAD02] [SMK*09][SBH*06] (Figure 12). Thus, we plan to apply our method to various shapes of real object surfaces, including 3D curved surfaces.

Finally, the distance between the observer's head and the real object surface was limited to approximately 50 cm. Through our several pilot studies, we are aware that appropriate density, dot size, and transparency of the random-dot mask may vary, depending on the features of the virtual object and the real object surface. Additionally we are also aware that it may be better to adjust the dot size of the mask in accordance with the distance between the observer's head and the real object surface (random-dot mask) so that the dots do not appear too big or too small in the observer's vision. Consequently, our future work includes establishing the random-dot mask design guidelines that can correspond to various features of the AR environment.



(a) with mask



(b) without mask

Figure 10: *View in experiment 2-2 (stereo pair; parallel)*

6. Conclusion

To improve transparency perception and depth perception in a stereoscopic AR environment, we proposed the method of adding a random-dot mask onto a real object surface. This method conveys to observers the effect of "stereoscopic pseudo-transparency," the illusion of observing the virtual object through many small holes. Based on our experiments, we demonstrated the potential effectiveness of the proposed method in improving depth perception between a real object surface and a virtual object in a stereoscopic AR environment.

The major contribution of our study is to show that seemingly obtrusive random-dot masks were effective in improving not only the anteroposterior relation between the surface and the virtual object, but also the distance between them.

For future work, we will tackle the remaining issues

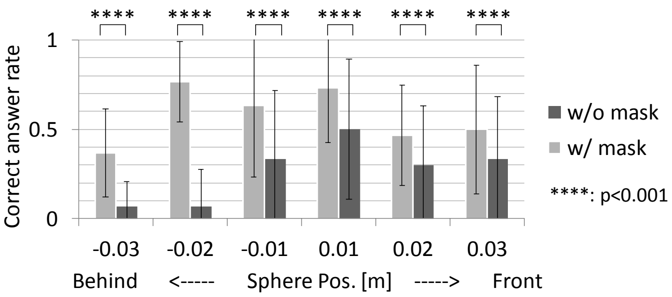


Figure 11: *Results of experiment 2-2: Correct answer rate between w/ and w/o mask at each position. Error bars represent standard deviation.*

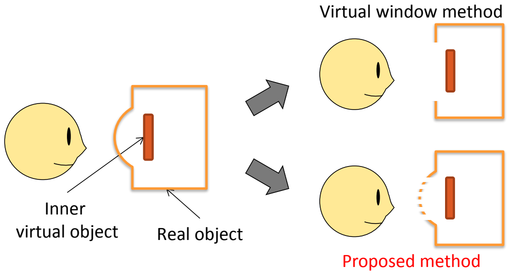


Figure 12: *Comparing between the virtual window method [FAD02][SMK*09][SBH*06] (upper right) and the proposed method (bottom right).*

described in section 5. In addition, we would like to test various devices such as optical see-through HMDs and video projectors, and improve our method so that it can be applied to various practical applications.

Acknowledgement

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