Depth Perception Characteristics in Plane Fog Screen

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ABSTRACT

We discuss the phenomenon that the projected image is not perceived at exact screen location when plane fog screen (PFS) is used in projector system, and the location of the perceived image depends on the observers position etc. It can be expected this phenomenon could be applied to 3D display in future.

1 Introduction

Glasses-free and less-fatigue 3D display with interaction capabilities is widely expected, and the studies for such 3D display is conducted for a long time. In addition, the interaction is recently expected without physical contact due to COVID-19. As an approach for this issue, we are studying an approach just using a plane fog screen (PFS) and a commercial projector. In this paper, we will introduce the depth perception characteristics on the approach.

The history of fog screen (FS) is not so long but gets attentions [1-6]. Rakkolainen et al. introduced walk-thru system using FS as the new experience and the walk-thru system was permanently installed at a museum [7]. In addition to this sort of 2D-display approaches, there are some approaches for 3D display. For example, Lee *et al*. introduced the combination of FS and DFD (Depth-Fused 3D) technology, where two FS and two projectors are necessary [8]. Yagi *et al*. studied the round-view cylindrical 3D display, where a cylindrical FS and some projectors are necessary [9]. These approaches need multiple projectors and non-simple FS for 3D display, and these requirements are feared to be a barrier to practical 3D display.

We are focusing on the phenomenon that the depth can be perceived even with one PFS and one projector [10]. In this paper, we show some evaluation results to clarify the characteristics of this depth perception in the system.

2 Projection System Using Plane Fog Screen (PFS)

2.1 Scattering by PFS

The intensity of scattering light depends on all the wavelength of light, the size of the particles and scattering direction. In general. when the particle size is much smaller than the wavelength of light, Rayleigh scattering occurs. When it is similar with the wavelength. Mie scattering occurs. Since the wavelength of visible light is about 400 nm-800 nm and the particle size of FS is about several tens of micrometers, Mie scattering dominantly occurs in FS projection system, and its forward scattering is strong due to Mie scattering. On this background, our interest is not front projection but back projection.

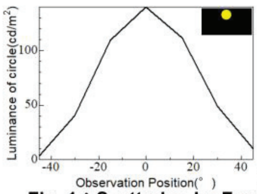


Fig. 1 : Scattering by Fog

Fig. 2 : Plane Fog Screen generator

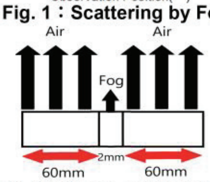


Fig. 3 : Cross section of PFS

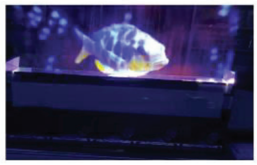


Fig. 4 : Example of projection

Fig. 1 shows the measured luminance in our actual back projection system that consists of PFS generator and a commercial projector. This result shows that the scattering light is strong for forward direction as we expected.

2.2 Projection System in This Paper

The projection system in this paper consists of a PFS generator and a commercial projector. The PFS generator was handmade, and was mainly fabricated by aluminum columns, USB-connected fans, and fog machines as shown in Fig. 2. It generated upward fog flow, and thin and flat fog flow was achieved by strong upward airflow along both sides of the fog flow (Fig. 3). Fig. 4 shows an example of projected image on the PFS; a swimming fish.

3 Experiments: Evaluation of depth perception in PFS

To clarify the depth perception characteristics in PFS, three experiments(Expt. 1-3) were prepared. Because the observer's position influences strongly to the depth perception, all experiments are carried out while changing the position. In this study, we clarify the depth perception characteristics while changing five variables such as observation position, thickness of PFS, spacing of images, luminance of circles in an image and luminance of overall image. The variables used for Expt.1-3 are summarized in Table 1.

The total number of subjects for all experiments was 7, including 3 subjects (2 males and 1 female) for Expt. 1 and 2, and 4 subjects (4 males) for Expt. 3. The subjects include both naïve and non-naïve for purpose of this study.

Table 1 : Variables for each experiment

Experiment	Variables
Expt.1 [Thickness of PFS]	**Thickness of PFS** [Thin:1.5 cm, Medium:4.5 cm, Thick:6.5 cm] Observation Positions [0°, 15°, 30°, 45°] Luminance of circles in an image (a)Similar lum. [Left: 118.5 cd/m², Right: 125.5 cd/m²] (b)Different lum. [Left: 110.5 cd/m², Right: 6.41 cd/m²]
Expt.2 [Spacing of circles]	**Spacing of circles** [Small:1.1 cm, Medium:4.5 cm, Large:11.0 cm] Observation Positions [0°, 15°, 30°, 45°] Luminance of circles in an image (a)Similar lum. [Left: 118.5 cd/m², Right: 125.5 cd/m²] (b)Different lum. [Left: 110.5 cd/m², Right: 6.41 cd/m²]
Expt.3 [Luminance of overall image]	**Luminance of overall image** I -[Low:115.6 cd/m², Middle:200.3 cd/m², High:637.8 cd/m²] II -[Low:42.5 cd/m², Middle:134.5 cd/m², High:632.5 cd/m²] Observation Positions [0°, 15°, 30°, 45°] Thickness of PFS [Expt.3-(a):2.5 cm, Expt.3-(b):1.5 cm]

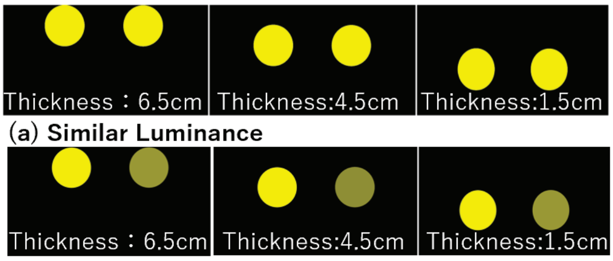
3.1 [Expt. 1 Thickness of PFS] Setup

In Expt. 1, we will clarify the influence of thickness of PFS and the luminance in an image to be displayed. Expt. 1 (a): Change the thickness of PFS in the projected area. The two circles are projected with the similar luminance. Expt. 1 (b): Change the thickness of PFS in the projected area. The two circles are projected with different luminance.

As shown in Fig. 5, this experiment uses two circles as stimuli. We prepared experimental stimuli with three kinds of thickness of PFS (Thin: 1.5 cm, Medium: 4.5 cm, and Thick: 6.5 cm) and two kinds of two circles (similar luminance and different luminance) as shown in Fig. 5(a), (b) and Table 2. Because the thickness of PFS was depending on the height of projection position, the upper circles (left image in Fig. 5(a)(b)) was for thick PFS and lower circles (right image in Fig. 5(a)(b)) is for thin PFS. The spacing of the projected circles was constant at 11.0 cm.

Observation positions were 0°,15°, 30° and 45° to the right from the front of PFS. The observation distance was 2.0 m (Fig. 6). In the experimental system, the area where the fog generator was covered by black plastic board so that the subjects could not see the exact location of PFS. Perceived depth was evaluated by the method shown below (following (1) through (4)).

(1) Immediately after the fog is emitted, move in an arc from the 0° position (in front of the PFS) to the observation position (0°, 15°, 30°, and 45° to the right) while watching the projected image with subject's eyes.
(2) Observe the projected image for 3 seconds after moving to each observation position
(3) After 3 seconds, the evaluation board is placed on the table near PFS generator and the subject places two markers at the perceived two circle's locations.
(4) Measure the distance of the two markers as the depth distance.



(a) Similar Luminance
(b) Different Luminance

Fig. 5 : Stimulus evaluating effects of thickness of PFS in Expt. 1

Table 2 : Difference in luminance of circles (Expt. 1,2)

	Expt. 1 (a) **Expt. 2 (a)**		**Expt. 1 (b)** **Expt. 2 (b)**	
	Left circle	Right circle	Left circle	Right circle
Luminance of circles (From the front)	118.5cd/m²	125.5cd/m²	110.5cd/m²	6.41cd/m²

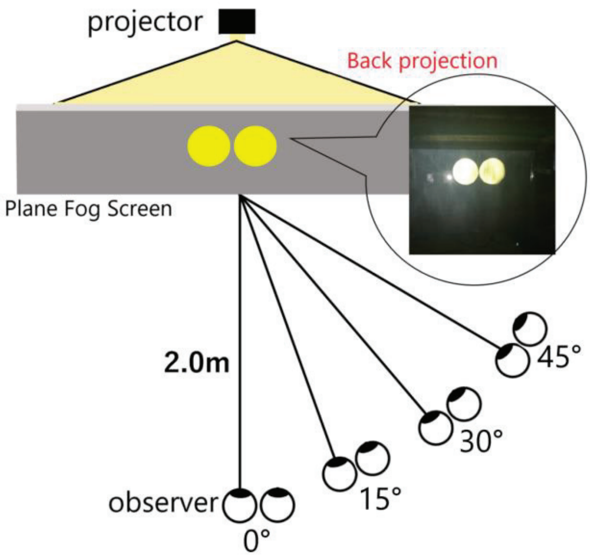
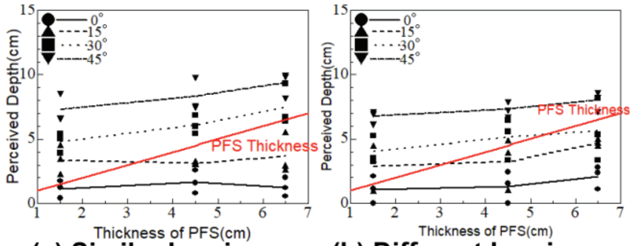


Fig. 6 : Experiment system

3.2 [Expt. 1 Thickness of PFS] Results

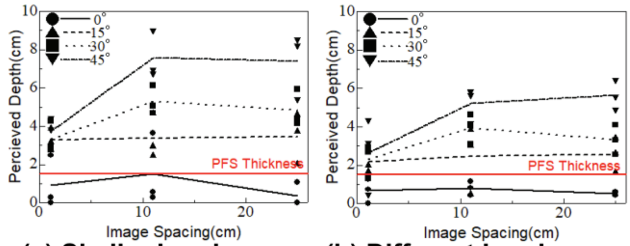
The results are shown in Fig. 7. Positive value of the vertical axis indicates that the left circle is perceived behind the right circle.

The Fig. 7(a) is the perceived depth when the left and right circles are the similar luminance, while the Fig. 7(b) is that when the left circle is brighter than right circle. According to the results in both cases, perceived depth was increased with increasing thickness of PFS, and this tendency became strong while observer moved to right side from 0°to 45°. There was an overall decreasing trend in depth in the results with images of different luminance of two circles.



(a) Similar Luminance (b) Different Luminance

Fig. 7 : Perceived depth for three different PFS thickness in Expt. 1



(a) Similar Luminance (b) Different Luminance

Fig. 9 : Perceived depth for three different spacing of the circles in Expt. 2

3.3 [Expt. 2 Spacing of circles] Setup

In Expt. 2, we will clarify the influence of both spacing of two circles and luminance difference of two circles on perceived depth. Expt. 2 (a): Change the spacing between the two circles. The two circles are projected with the similar luminance. Expt. 2 (b): Change the spacing between the two circles. The two circles are projected with different luminance.

We prepared experimental stimuli with three different spacing of circles (Small: 1.1 cm, Medium: 4.5 cm, and Large: 11.0 cm) and the two luminance types of two circles (similar luminance and different luminance) as shown in Fig. 8 and Table 2. The thickness of the PFS was constant at 1.5 cm. Other experimental setup were the same as in Expt. 1.

(a) Similar Luminance

(b) Different Luminance

Fig. 8 : Stimulus for evaluating effects of spacing between two circles in Expt. 2

3.4 [Expt. 2 Spacing of circles] Results

The results are shown in Fig. 9. Positive value of the vertical axis indicates that the left circle is perceived behind the right circle.

The Fig. 9 (a) is the result that the left and right circles are similar luminance, while the Fig. 9 (b) is the result that the left circle is brighter. According to the results in both cases, when the spacing of two circles was increased, the perceived depth tended to increase up to 10 cm at the observation position of 15°, 30°, and 45° to the right, except at 0°, but above 10 cm, the perceived depth tended to saturate. Similar to the results of Expt. 1, there was an overall decreasing trend in depth in the results with images of different luminance of two circles.

3.5 [Expt. 3 Luminance of overall image] Setup

In Expt. 3 (a) and (b), we will clarify the influence of the luminance of overall image projected onto the PFS.

We projected an image while changing the luminance of overall image (Low: 115.6 cd/m^2, Middle: 200.3 cd/m^2, and High: 637.8 cd/m^2) by brightness control function in the projector. (Table 3). The thickness of the PFS was set to 2.5 cm in Expt. 3(a) and 1.5 cm in Expt. 3(b), by changing the projecting position on PFS, and the spacing of two circles was fixed at 11.0 cm. Other experimental setup were the same as in Expt. 1.

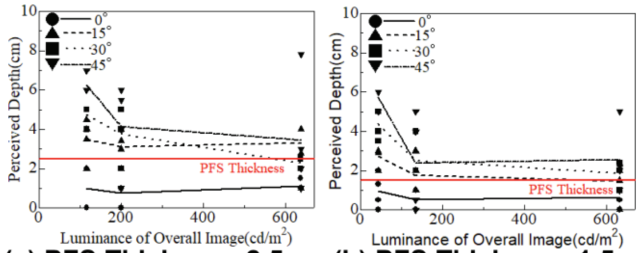
Table 3 : Details of stimuli used in Expt.3

Image 	Expt. 3 (a)			Expt. 3 (b)		
Luminance of circles (From the front)	Low	Middle	High	Low	Middle	High
	115.6 cd/m²	200.3 cd/m²	637.8 cd/m²	42.50 cd/m²	134.5 cd/m²	632.5 cd/m²
Spacing of two circles	11.0cm			11.0cm		
Thickness of the PFS	2.5cm			1.5cm		

3.6 [Expt. 3 Luminance of overall image] Results

The results are shown in Fig. 10. Positive value of the vertical axis indicates that the left circle is perceived behind the right circle.

As shown in Fig. 10, when the luminance of overall image increased, perceived depth tended to decrease at all observation positions (0°, 15°, 30°, and 45° to the right). While a maximum depth perception of approximately 7 cm was achieved at the lowest luminance around 100 cd/m², depth perception tended to decrease significantly when projecting at 200 to 600 cd/m². Comparing Expt. 3(a) and (b), perceived depth was increased when thickness of PFS was increased.



(a) PFS Thickness 2.5cm (b) PFS Thickness 1.5cm

Fig. 10 : Perceived depth for three different luminance levels in Expt. 3

4 Discussion

4.1 Influence of Observation Angle, Thickness of PFS, and Spacing of Circles

From the results of the Expt. 1 to 3, it was clarified that the most influential factor in depth perception is the observation angle. In Fig. 11, the results of Expt. 1(a) are replotted as a function of the observation angle. When the observation position was changed from 0° to 45°, the perceived depth increased from 2 cm to 10 cm.

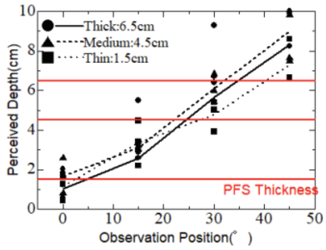


Fig. 11 : Perceived depth in Expt. 1(a) as a function of observation angle

According to Expt. 1, the perceived depth was increased with increasing the thickness of the PFS in the projection area as shown in Fig. 7 and Fig. 10. Expt.2 revealed that the spacing of two circles also affects the perceived depth as shown in Fig. 9.

These findings suggest that when using PFS as a 3D display, these parameters should be taken into account: the observation angle, the thickness of the PFS, and the spacing of objects in the projected image. At the same time, it is expected that effective 3D expression will be possible by appropriately controlling these parameters.

4.2 Influence of Luminance Difference of Circles in an Image

In this study, the right circle was always perceived in the foreground and the left circle was perceived in the back, as shown by the fact that all perceived depths are plotted with positive value. Therefore, we tried to reverse the order of depth by reducing the luminance of the right circle significantly from the luminance of the left circle, because the luminance is one of the pictorial cues of depth perception. However, comparing Fig. 7 (a) and (b) and Fig. 9 (a) and (b), the depth order was not reversed, and only the decrease about 2 cm in depth was observed. This suggests that the effect of the luminance difference on the depth perception on PFS is limited, and that other factors such as the observation angle have a large effect.

4.3 Influence of Luminance of Overall Image

According to Fig. 10 (a) and (b), a significant decrease in depth perception was observed as the luminance of projected overall image increased. As luminance of overall image increased in the range of approximately 100 cd/m² to 200 cd/m², perceived depth was decreased. However, the perceived depth remained constant when the luminance of overall image is above 200 cd/m^2. Fig. 12 shows that the projected image at low and high luminance. When luminance of overall image was high, some subjects reported that circles seemed to sticked on PFS surface by the conspicuous white color of the fog, making it difficult to perceive depth. If depth perception and natural aerial images is to be achieved, we need to reduce luminance to a certain degree to reduce the visibility of the fog itself.

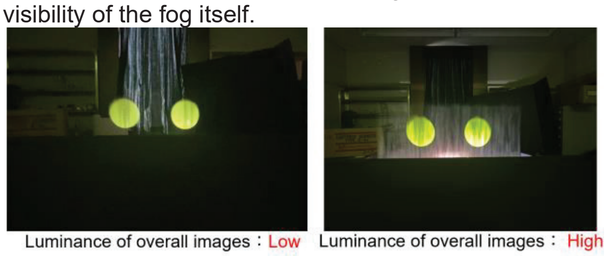


Fig. 12 : Difference of projected image in Expt. 3

5 Conclusion

We evaluated the depth perception characteristics of the projection system that consists of a plane fog screen (PFS) and a commercial projector. According to experimental results, the more the observation position become away from the front of PFS, the more we perceive the depth on the objects in the projected image. As well as the observation position, the thickness of PFS, spacing of projected objects, and image luminance of overall image influence to the depth perception. In future, we will discuss the 3D display using a PFS and a commercial projector that is based on the experimental results in this paper.

Acknowledgment

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