# Visual Discomfort of Transparent LCDs for Mixed Reality Applications

Yan-Min Chen, Pei-Li Sun

National Taiwan University of Science and Technology, Taipei 10607, Taiwan

**Keywords**: Transparent display, Augmented reality, Visual discomfort, Binocular rivalry

**ABSTRACT**

*In mixed reality applications of flat panel transparent displays, binocular rivalry is the main reason causing visual discomfort. A series of psycho-visual experiments were conducted to scale the visual discomfort of a transparent LCD in different viewing conditions and a masking method is proposed and tested to reduce the unpleasant ghosting effect.*

## 1. INTRODUCTION

In recent years, AR/VR applications become widespread. Mixed reality (MR), which brings together the physical and digital world, is potentially a good way to expend the market of transparent displays. However, it suffers from huge binocular parallax [1][2] between the behind object and the overlaid virtual pattern. Human visual system uses accommodation and convergence to determine how the images of two eyes are combined. Referring to **Fig.1 (a)**, when an observer accommodates and converges on the near transparent display, the virtual pattern will be clear but the distant real object would become duplicated ghost images (**Fig.1 (b)**) [3]. In contrast, if the observer accommodates and converges on the behind real object, the virtual pattern would become duplicated ghost images (**Fig.1 (c)**). The huge image differences between the two eyes would cause binocular rivalry [4][5] which is the main source of visual discomfort.

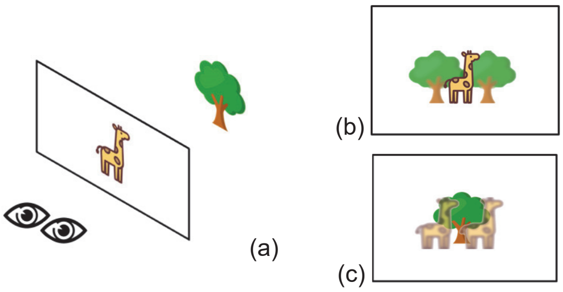


**Fig.1 (a) MR Viewing environment of a transparent display, (b) look at the display image, (c) look at the behind object.**

To further explore this issue, a series of psycho-visual experiments was carry out to scale the visual discomfort of a transparent LCD in different viewing conditions. The variables include viewing mode (monocular/binocular view), screen-to-object distance, image content (pattern), contrast of the virtual pattern and the mask methods. A 47-inch full color transparent LCD display was used for the visual experiments (**Fig.2**). Participants would see the scene which blended the virtual pattern shown on the display and the behind target shown on a cell phone in each experimental condition. The visual comfort score was recorded by a research assistant after each condition presented. The experimental data were analyzed by Torgerson's law of categorical judgement [6].

**Fig. 2 Viewing environment of the study.**

Four visual experiments have been done in this study:

**Exp.1** Visual discomfort of different viewing models: use monocular viewing model as a reference point, scale the scores of visual discomfort relatively in different binocular viewing models.

**Exp.2** Visual comfort of monocular masking: observer accommodates on the behind target, evaluate the visual comfort of binocular viewing with an on-screen rectangle mask to reduce the visibility of one eye.

**Exp.3** Visual comfort of image contrast: evaluate the visual comfort of binocular viewing with 3 levels of image contrast shown on the transparent display.

**Exp.4** Visual attention of image blurring: apply image blurring to either the transparent pattern or the background target to see if the blurriness will affect the visual attention.

The experimental setup and results will be introduced in the following sections:

## 2. EXP.1: VISUAL DISCOMFORT OF DIFFERENT VIEWING MODELS

### 2.1 Experimental setup

The aims of Exp1. are to answer the following questions:

(1) If binocular viewing would cause visual discomfort? (2) What is the acceptable threshold of screen-to-object distance? (3) In the binocular viewing, if the observer uses his/her dominant eye to align the screen pattern to the behind target is better than the use of non-dominant eye? (4) In terms of the pattern, if the visual discomfort of a frame (to highlight the target) is lower than a striped pattern (to cover the target)?

To answer these questions, a 47-inch transparent LCD display was used to display the patterns and a 4.7-inch (500 cd/m$^2$ white point) cell phone display was used to show the behind target. To make the screen pattern visible, a white projection screen was behind the cell phone and two high power LED matrices provide enough reflection light to pass through the transparent display (**Fig.2**). The eye-to-screen distance in Exp.1 was 100cm. The screen-to-object distance varied from 5cm to 40cm in 5cm interval. The factors of the experiment include: (1) eye-alignment (dominant vs. non-dominant eye), (2) image content (frame vs. strip), (3) screen-to-object distance (5cm to 40cm). 10 observers (age 24 on average) anticipated to the experiment. They all passed Stereo Optical's Stereo Randot Test and used Hole-in-the Card Test to determine their dominant eye. Referring to **Fig.3**, T1 pattern was used as the target image and the P1 and P2 patterns used as the frame and striped patterns respectively.

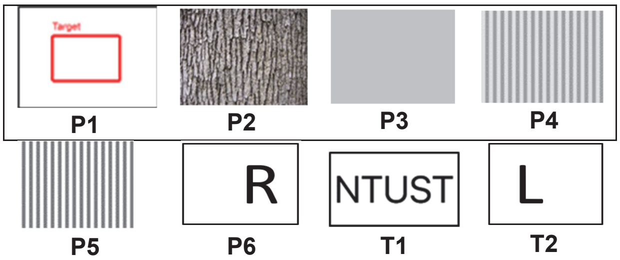


**Fig.3 Test patterns.**

For each screen-to-object distance, observer performed the following tasks:

(1) Listen to the research assistant for experiment instruction.
(2) Put his/her own head on a head holder to fix the eye position.
(3) Show the on-screen pattern.
(4) Open one eye, use mouse to adjust the on-screen pattern to match the 2D location of the behind object.
(5) Look at the object and the pattern back and forth for 5 seconds.
(6) Remember the visual discomfort level of in the monocular viewing mode.
(7) Open the other eye, look at the object and pattern back and forth for 5 seconds.
(8) In the binocular viewing mode, reporting the score of visual discomfort related to the monocular viewing mode in ITU-R BT.500-11 five-grade impairment scale. The grades are: 1-imperceptible, 2-perceptible but not annoying, 3-slightly annoying, 4-annoying and 5-very annoying.

## 2.2 Results

### 2.2.1 Screen-to-object distance

The Z-scores for different screen-to-object distances analysed by Torgerson's law of categorical judgement are shown in **Fig.4**. The error bars represent 95% confidence intervals. As can be seen, the visual discomfort becomes more annoying when the screen-to-object distance increased. The reason is the distance positively related to binocular image difference of the on-screen pattern. The image difference will induce unpleasant binocular rivalry. The blue lines in **Fig.4** are the boundary of each grade category. The acceptable threshold there is around 20 cm as the grade 1 and 2 are "not annoying". The 20 cm is equivalent to 36' (0.6°) of binocular parallax on the two sides of the behind object.

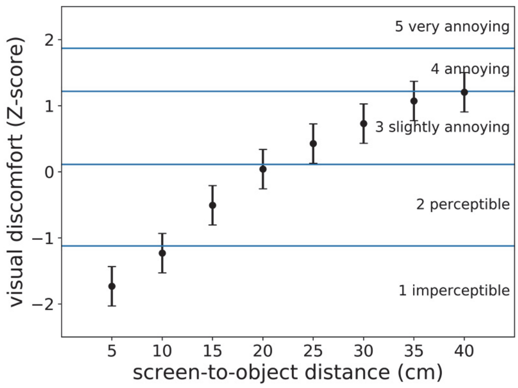


**Fig.4 The effect of screen-to-object distance on visual discomfort.**

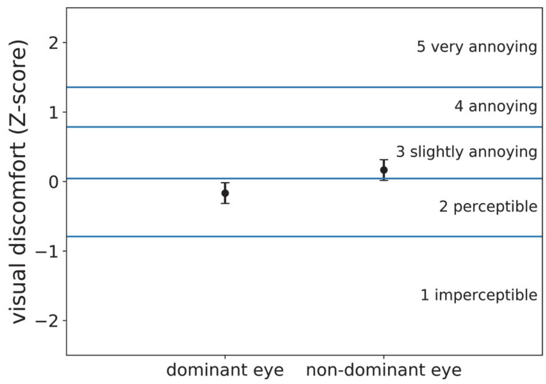


**Fig.5 The effect of dominant eye-alignment on visual discomfort.**

### 2.2.2 Eye-alignment

In the step 4 of the observer tasks, if the observer used his/her dominant eye to match the on-screen pattern to the behind object, the score of visual discomfort reduces a bit (**Fig.5**) according to the data analysis.

2.2.3 Image content

Referring to **Fig. 6**, the results show the visual discomfort of a frame (to highlight the target) is slightly higher than a striped pattern (to cover the target). The reason could be that the image contrast of the frame pattern is higher than the striped pattern, ghosting effect is more significant by using a frame compared to a regular pattern.

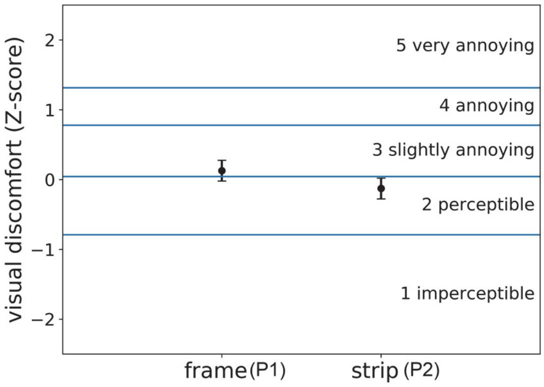


**Fig.6 The effect of on-screen pattern on visual discomfort.**

2.2.4 Factor analysis

The experiment data also analyzed by multivariate analysis of variance. The results show at 95% confidence level, all of the 3 factors: screen-to-object distance, eye-alignment and image content have significant impact on the visual discomfort. However, no interaction among the 3 factors.

2.2.5 Summary

Based the experimental results, the answer of the questions in Section 2.1 are: (1) Binocular viewing would cause visual discomfort significantly when the screen-to-object distance is far, (2) The acceptable threshold of screen-to-object distance is about 20 cm when the eye-to-screen distance is 100 cm, (3) Using dominant eye to align the screen pattern to the behind target is better. (4) In terms of the pattern, a frame is worse than a striped pattern.

## 3. EXP.2: VISUAL COMFORT OF MONOCULAR MASKING

### 3.1 Experimental setup

Applying a low-transparency mask to block the ghost target image in one view would reduce the visual discomfort compared to binocular viewing which induces the ghosting effect. The aim of Exp.2 is to proof this idea. The experimental setup was similar to the Exp.1 but the eye-to-screen distance was 45cm. It will result in stronger visual discomfort, and when the observer looks at the behind object, the on-screen pattern will totally separate so as to have to change to block one-view for the double ghosting images. The factors of the experiment include: (1) density of on-screen mask (100%(black), 50%(gray), 0%(transparent)), (2) eye-alignment (dominant vs. non-dominant eye), (3) image content (frame vs. strip), (4) screen-to-object distance (15cm, 30cm and 45cm). 10 observers (age 24 on average) anticipated to the experiment. Referring to **Fig.3**, T1 pattern was used as the target image and the P1 and P2 patterns used as the frame and striped patterns respectively.

For each factor combinations, observer performed the following tasks:

(1) Listen to the research assistant for experiment instruction.
(2) Put the head on a head holder to fix the eye position.
(3) Show the on-screen pattern.
(4) Open one eye, use mouse to adjust the on-screen pattern to match the 2D location of the behind object.
(5) Open the other eye, look at the behind object.
(6) Report the score of visual comfort in five-grade scale. The grades are: 1-bad, 2-poor, 3-fair, 4-good and 5-excellent.

### 3.2 Results

The mean results are shown in **Fig.7**. As can be seen, the scores of visual comfort are higher when a mask block one view. Using 50% (gray) mask is better than 100% (black) mask, and both of them are better than 0% (transparent) mask.

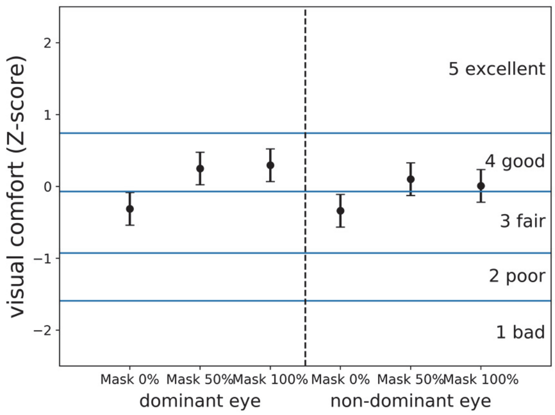


**Fig.7 The effect of monocular mask density and screen-to-object distance on visual comfort.**

The experiment data also analyzed by multivariate analysis of variance. The results show at 95% confidence level, only the density of on-screen mask and the screen-to-object distance have significant effect on the visual comfort. No interaction among the 4 factors. We found that when we block one-view, the other eye will do the alignment automatically. It means that "which eye is the dominant eye?" is not important in this case.

## 4. EXP.3: VISUAL COMFORT OF IMAGE CONTRAST

### 4.1 Experimental setup

The aim of Exp3. is to see if image contrast of the on-screen pattern affects the visual comfort when the pattern overlays the behind object. The on-screen patterns used in Exp.3 are P3, P4 and P5 in **Fig.3**. T1 again used as the behind target. The factors of the experiment include: (1) image contrast: low (a gray color patch), middle and high, (2) density of on-screen mask (100%(black), and 0%(transparent)), and (3) eye-alignment (dominant vs. non-dominant eye). The experimental setup is very similar to that of Exp.2. Both the eye-to-screen and the screen-to-object distances were 45cm.

### 4.2 Results

The mean results are shown in **Fig.8.** As can be seen, the lowest image contrast of the on-screen pattern (P3, using gray color patch) got the highest score. It suggests that if no texture on the pattern, observer can look at the behind object without visual distraction from the on-screen pattern. However, this kind of pattern cannot add more information (except color) to the object.

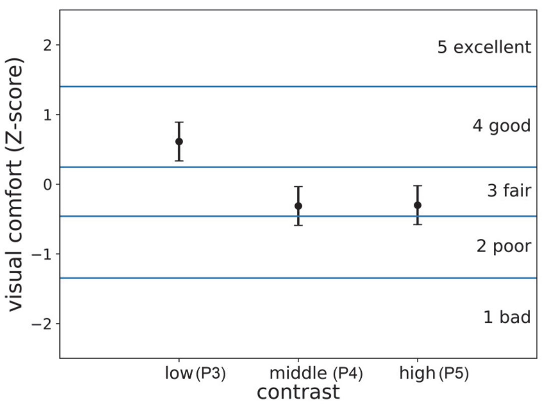


**Fig.8 The effect of image contrast of the no-screen pattern on visual comfort.**

## 5. EXP.4: VISUAL ATTENTION OF IMAGE BLURRING

The aims of Exp.4 is to know, in the AR viewing environment, if human eyes will look at the sharpest layer like camera autofocus. To this end, we use a big character as test image, blur the image in 3 levels using 2D Gaussian spatial filtering. Referring to **Fig.3**, P6 and T2 were chosen as the on-screen pattern and the behind target, respectively. There are 3 factors in the Exp.4, including (1) 3-level Gaussian blurring for the on-screen pattern, (2) 3-level Gaussian blurring for the behind target, and (3) eye-alignment (dominant vs. non-dominant eye). The experimental setup was similar to that of Exp.3 except Exp.4 asked the observers to report "which layer (screen or target) pay you more attention?". Referring to **Fig. 9**, the results show that human eyes will look at the sharpest layer like camera autofocus. When both of them are blur, observers will look at the screen layer (foreground).

## 6. CONCLUSIONS

A series of psycho-visual experiments were conducted to scale the visual discomfort of a transparent LCD in different viewing conditions. The results show that binocular viewing would cause visual discomfort significantly when the screen-to-object distance is far. The acceptable threshold of screen-to-object distance is about 20 cm when the eye-to-screen distance is 100 cm. The visual comfort of pattern-to-target image alignment for the dominant eye is slightly higher than the non-dominant eye. The results also show that applied a low-transparency mask to block the ghost target image in one view would reduce the visual discomfort compared to binocular viewing which induces the ghosting effect. In terms of the on-screen pattern, low contrast is preferred. In addition, human eyes intent to look at the sharpest layer like camera autofocus. The findings are useful for improving the visual comfort of flat panel transparent display for mixed reality applications.

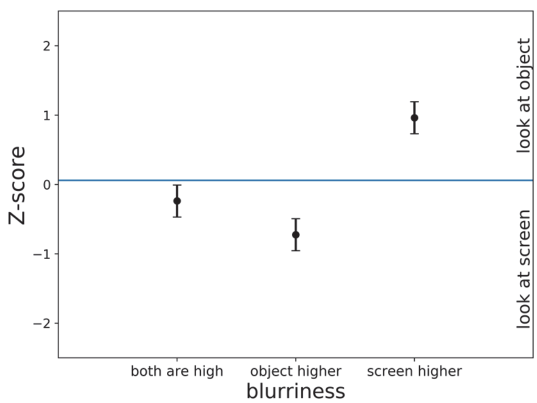


**Fig.9 The effect of image blurriness on visual attention.**

## REFERENCES

[1] J. H. Lee et al. "Binocular Cursor: Enabling Selection on Transparent on Transparent Displays Troubled by Binocular Parallax. CHI 2013.

[2] J. H. Lee et al. "Transparent Display Interaction without Binocular Parallax" ACM 2012.

[3] M. T.M Lambooij et al. "Visual Discomfort in Stereoscopic Displays: A Review" SPIE 2007.

[4] T. HANDA et al. " Effects of Dominant and Nondominant Eyes in Binocular Rivalry" Optometry and vision science. VOL. 81, NO. 5, PP. 377–382 2004.

[5] S. Knorr "Basic Rules for Good 3D and Avoidance of Visual Discomfort." 2011.

[6] W. S. Torgerson, "A Law of Categorical Judgment", Consumer Behaviour, L. H. Clark (ed.), New York University Press, New York, 92–93, 1954.