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Comparison of Measures of Blurriness in Transparent Displays

Chang-Mo Yang, Dong-Hyeok Lee, Kyoung-Soo Park, Young-Tae Kim, and Choon-Woo Kim
Dept. of Information & Communication Eng., Inha University, Incheon, Korea

Abstract

Transparent displays allow observers to see the objects behind the displays as well as information on the displays. See-through capability is one of the most important performance indices of transparent display. It is often called as blurriness of transparent display. This paper presents performance evaluations of the various measures of blurriness designed to describe the see-through capability of transparent display. Performance of the measures was evaluated by comparing values of measures with results from human visual experiments.

1. Introduction

Transparent displays have received attention as next-generation displays. They can be based on the liquid crystal display (LCD) or organic light emitting diode (OLED) technologies [1]-[8]. Transparent displays allow observers to see the objects behind the displays as well as information on the displays. Therefore, see-through capability is one of the most important performance indices of transparent display.

The performance of transparent plastics is characterized by the luminous transmittance factor and haze [9]-[10]. The transmittance factor is the ratio of the luminous flux transmitted through a transparent plastic. The haze of transparent display is defined as the ratio of the transmitted light that is scattered so that its direction deviates more than 0.044 rad or 2.5° from the direction of the incident light [10].

See-through capability of transparent display, often called as blurriness, is mainly affected by the haze and background distance that represents the distance between transparent display and an object behind the display. For example, as the value of haze or background distance increases, the blurriness in the transmitted image is increased. Therefore, the haze is not enough to fully describe see-through capability of transparent display.

Recently, quantitative measures to represent degree of blurriness in the transmitted images are reported [10]-[12]. The first measure is called as 'Purity' [10]. The ratio of the transmitted light within 2° from the direction of the incident light is defined as 'Purity'. As an alternative to the haze, it was designed to describe degree of blurriness due to light diffusion for a fixed background distance. The second measure is called 'Clarity' in [11]. A black-to-white square wave is utilized as an object behind transparent display. The transmitted luminance of the square wave is measured. Due to the blurriness of transparent display, the square wave will be changed into sinusoidal wave. The value of 'Clarity' is calculated based on blurred width in sinusoidal wave.

The last one is a measure based on Gaussian blur model [12]. Blurriness of transparent display is represented by standard deviation of Gaussian blur model. Luminance of black/white patch passed through transparent display is measured. Next, standard deviation of Gaussian blur model is estimated based on the measured luminance transition curve by minimizing the difference between the measured luminance transition curve and results of convolution of the step function and Gaussian blur models.

Objective of this paper is to compare performances of the aforementioned measures of blurriness proposed for the transmitted image through transparent displays. An ideal measure of blurriness should exactly match with perceived degree of blurriness by human vision. Therefore, performance of the measures is evaluated by comparing calculated values of the measures and results from human visual experiments. Correlation coefficients between the calculated values of the measures and results from human visual experiments are calculated.

The various sample images representing different combinations of values of the haze and background distances are utilized for human visual experiments. Paired comparison is employed in human visual experiments [13]. Observers are asked to choose an image with higher degree of perceived blur. Results of the paired comparisons are converted into the JND units [14].

In Section 2, human visual experiments to compare the accuracy of the measures are explained. In Section 3, performance of the measures is evaluated by comparing calculated values of the measures and results of human visual experiments. Finally, Section 4 concludes this paper.

2. Design of Human Visual Experiments

Perceived blurriness of the transmitted image through transparent display is derived by human visual experiments. Test images representing different degrees of blurriness are simulated and utilized for the human visual experiments.

2.1 Simulation of Test Images

Blurriness of the transmitted images through transparent display depends on the values of haze and background distance. In order to examine whether values of the blurriness measures correlate well with the results from human visual experiments, a number of transmitted images exhibiting different degrees of blurriness is prepared first. In this paper, three transparent plastics with different values of haze are utilized for test image simulation. Their values of haze are 7, 80 and 99%. Figure 1 illustrates a block diagram to generate simulation images for human visual experiments. For each of transparent plastics, luminance transition curves are measured for different values of background distance.

The black-and-white patch is displayed on an OLED display and utilized as an object behind transparent display as illustrated in Figure 2. Instead of hard copy object, an OLED display is utilized because of its wide dynamic range. The measurements are made along the red dots in Figure 2 using the two-dimensional spectroradiometer in a dark room to avoid flare effect. The spectroradiometer is aligned with the monitor and transparent plastic. Number of background distances for the luminance transition curve measurements are 6, 6 and 50 for the three transparent plastics with haze 7, 80 and 99%, respectively. Therefore, the number of luminance transition curves that are measure by the experimental setting in Figure 2 are 62

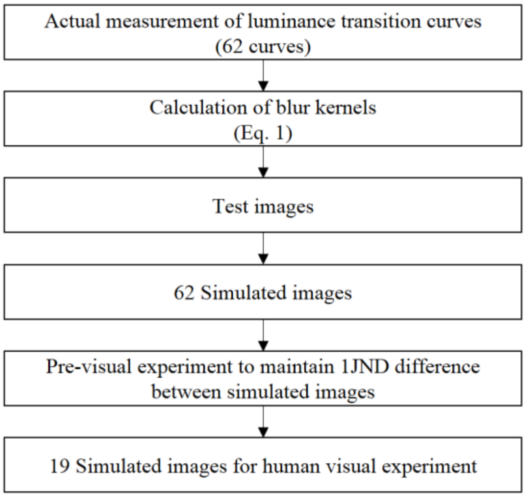


Figure 1. Flowchart of test image generation

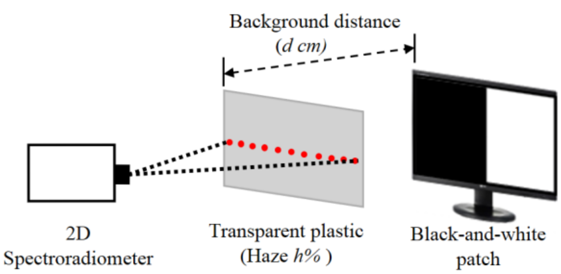


Figure. 2. Measurement condition for the luminance transition curves.

The measured values of luminance are normalized to be in the range of 0 and 1. Figure 3 illustrates examples of the measured luminance transition curves. Suppose that measured luminance transition curve for value of haze h % and background distance d cm is denoted by a 1×M vector $\mathbf{L}_{h,d}$. The blur kernel that yields the measured luminance transition curve is calculated by (1)

$$\mathbf{P}_{h,d} = \mathbf{T}^{-1}\mathbf{L}_{h,d} \quad (1)$$

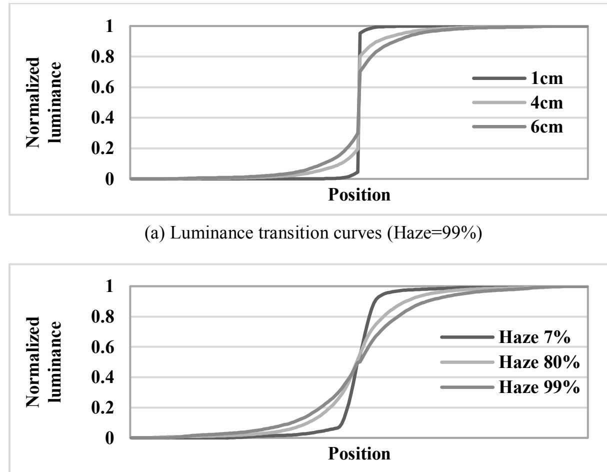
where $\mathbf{T}^{-1}$ is the inverse of the Toeplitz matrix. $\mathbf{T}$ is a M×M Toeplitz matrix and defined as

$$\mathbf{T} = \begin{bmatrix} 0 & 0 & 0 & \cdots & & & 1 \\ 0 & 0 & 0 & \cdots & & & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 1 & 1 & \cdots & & & 1 \\ 1 & 1 & 1 & \cdots & & & 1 \end{bmatrix} \quad (2)$$

$\mathbf{L}_{h,d}$ is measured luminance transition curve. $\mathbf{P}_{h,d}$ represents a blur kernel for the value of haze h % and background distance d cm. When $\mathbf{P}_{h,d}$ is applied to the black-and-white patch, the measured luminance transition curve for value of haze h % and background distance d cm can be exactly reconstructed without any error.

Suppose that 62 test images are arranged in the order of the perceived blurriness. In order to perform human visual experiments, it is not desirable that the difference in the perceived blurriness between two adjacent test images is so distinct that comparison of blurriness is obvious. It is also not desirable that difference in the perceived blurriness is so small that most of participants can not distinguish the difference. As illustrated in Figure 1, pre-visual experiments are performed in this paper to maintain the difference in perceived blurriness between two adjacent test images is about 1 JND (Just Noticeable Difference) unit [14]. As a result of the pre-visual experiments, nineteen combinations of the haze and background distances are selected from 62 combinations generated using three different transparent plastics. Table 1 lists the nineteen combinations the haze and background distance. The smaller value of the index in Table 1 indicates the smaller perceived blurriness. It can be noticed that the blurriness in the transmitted image is increased, as the value of haze or background distance increases. Of course, effect of the background distance on the perceived blurriness depends on the value of haze. For example, the perceived blurriness is more sensitive to the changes in the background distances when the value of haze is higher.

Four different test images illustrated in Figure 4 are utilized for the human visual experiments. For each of the four images in Figure 4, nineteen images exhibiting different degrees of the perceived blurriness are generated by the blur kernel calculated from the luminance transition curves. Figure 5 illustrates the examples of test images utilized for the human visual experiments.



(a) Luminance transition curves (Haze=99%)

(b) Luminance transition curves (Background distance=10cm)

Figure. 3. Measured luminance transition curves.

2.2 Viewing Conditions for Visual Experiments

Human visual experiments are performed under normal office viewing conditions. Intensity of illumination on surface of a display is 400lux. A 24 inch LCD display with 1920x1080 pixels is utilized for visual experiments. Distance from display to observer is 50 cm. Twenty observers consisting of 10 male and 10 female university students with normal corrected vision are participated in visual experiments.

2.3 Human Visual Experiments

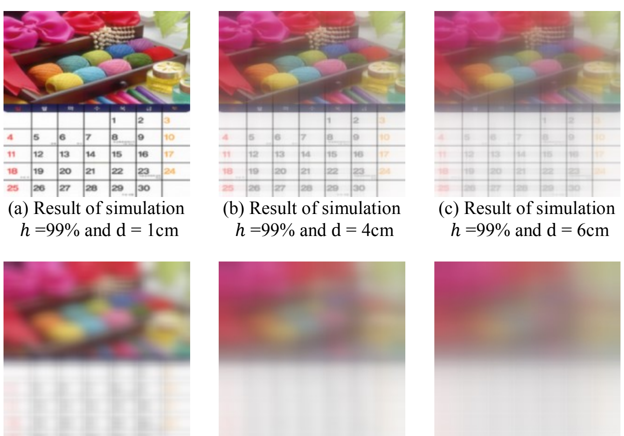
The nineteen test images exhibiting different degrees of the perceived blurriness are utilized for paired comparisons [13]. Therefore, each observer makes 684(=4 test images×${}_{19}C_2$) visual comparisons. Two images exhibiting different levels of blurriness are given to observers. Figure 6 illustrates an example of user interface for the human visual experiments. Observers are asked to choose an image with the higher perceived blurriness. The selected image receives a score of 1 and the other receives a score of 0. When

Table 1. Values of haze and background distances for nineteen combinations selected for human visual experiments

Index	Haze/Background distance	Index	Haze/Background distance
1	99%/1cm	11	80%/40cm
2	99%/4cm	12	99%/16cm
3	99%/5cm	13	80%/50cm
4	99%/6cm	14	99%/23cm
5	7%/10cm	15	99%/26cm
6	80%/10cm	16	99%/35cm
7	99%/10cm	17	99%/38cm
8	99%/13cm	18	99%/42cm
9	80%/20cm	19	99%/43cm
10	80%/30cm		

(a) Image 1 (b) Image 2 (c) Image 3 (d) Image 4

Figure. 4. Test images utilized in human visual experiments.



(a) Result of simulation h =99% and d = 1cm
(b) Result of simulation h =99% and d = 4cm
(c) Result of simulation h =99% and d = 6cm
(d) Result of simulation h =7% and d = 10cm
(e) Result of simulation h =80% and d = 10cm
(f) Result of simulation h =99% and d = 10cm

Figure. 5. Examples of simulation of transmitted images.

judged as the same level, both receive a score of 0.5. Subjective scores of human visual experiments are calculated by the Case V of Thurstone's law of comparative judgments [14]. Also, subjective scores are converted to JND [14].

3. Performance of Measures

Three different quantitative measures, 'Purity' [10], 'Clarity' [11] and standard deviation of Gaussian blur kernel [12] are calculated for each of the nineteen combinations of the haze and background distances used in human visual experiments. For three transparent plastics, the values of 'Purity' are obtained by the procedure

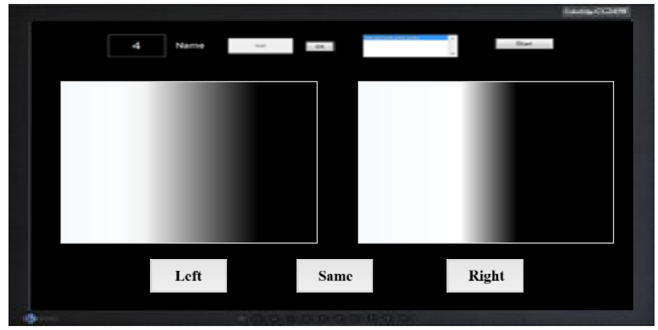


Figure. 6 Example of user interface for human visual experiments.

specified in [15]. In order calculate 'Clarity', the nineteen blur kernels obtained by (1) are applied to a black-to-white square wave. The standard deviations of Gaussian blur kernel are estimated by the procedure specified in [12] using the measured luminance transition curves of the black and white patch.

An ideal measure should exactly match with the perceived blurriness level of human vision. Therefore, performances of the measures [10]-[12] can be evaluated by comparing the calculated values of the measures and results from the human visual experiments. It should be mentioned that 'Purity' [10] represents the effect of haze on the perceived blurriness. Therefore, the values of 'Purity' remain unchanged for different background distances. As listed in Table 1, there are three test images with different values of haze. Therefore, the remaining two measures in [11] and [12] are compared with the results of the human visual experiments.

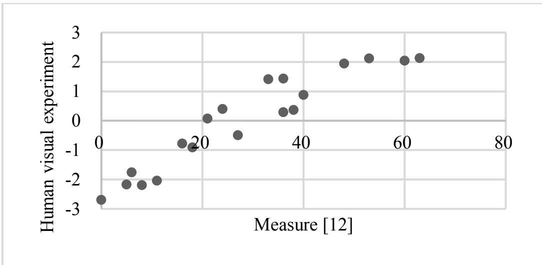
Pearson correlation coefficients between the calculated values of the measures [11]-[12] and the results of paired comparisons are calculated. The values of Pearson correlation coefficients are listed in Table 2. The calculated correlation coefficients can be regarded as a performance index to represent the accuracy of the measure. The standard deviation of Gaussian blur [12] yields the higher values of the correlation coefficient for all of four different test images in Figure 4.

'Clarity' [11] results in average correlation coefficients of 0.60. It should be mentioned that 'Clarity' [11] may not be suitable to represent wide range of the perceived blurriness ranging from Figure 5 (a) to (f). However, it may be utilized to describe the degree of the perceived blurriness in the range illustrated in Figure 5 (a) and (b).

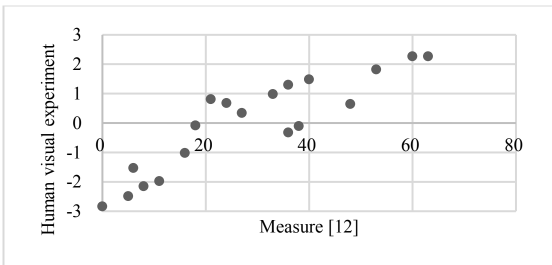
Table 2. Correlation coefficients between the calculated values of measures and results of human visual experiments

	Image1	Image 2	Image 3	Image 4	Average
Clarity [11]	0.60	0.62	0.59	0.61	0.60
Measure [12]	0.95	0.90	0.92	0.95	0.93

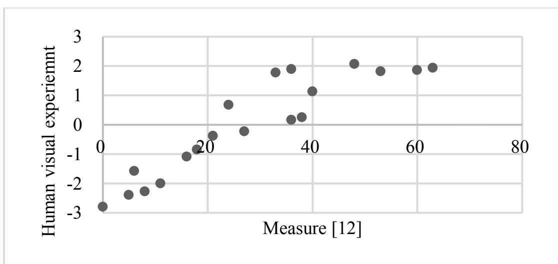
Figure 7 illustrates the plot of the standard deviation of Gaussian blur kernel [12] and the results from human visual experiments performed on the four images in Figure 4. The horizontal axis of Figure 7 represents the values of the standard deviation of Gaussian blur kernel [12]. The vertical axis denotes the results of the paired comparisons in the JND units.



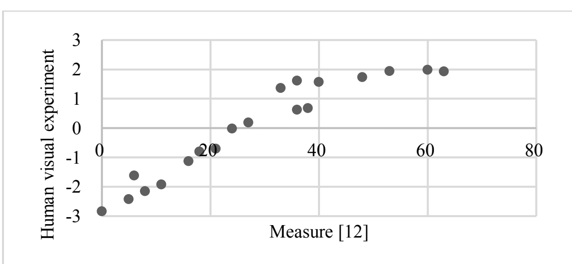
(a) Image1



(b) Image2



(c) Image3



(d) Image 4

Figure. 7. Plot of the measure [12] and results of human visual experiments.

4. Conclusion

Transparent displays have received attentions as next-generation displays. In the transparent OLED displays, the perceived image contains the information on the displays overlapped with the image of the objects behind displays. When attached to transparent OLED displays, transparent plastics can control transmission of incident lights and blurriness of transmitted image. They can extend the use of transparent OLED displays to various applications. Various efforts have been reported to quantitatively represent degree of blurriness in the transmitted images of the OLED transparent displays. This paper presents performance evaluations of the the measures designed to describe the blurriness. Human visual experiments are performed to compare the accuracy of the measures. The nineteen samples with different combinations of the haze and background distances are utilized for human visual experiments. Paired comparison is employed in human visual experiments. In addition, Purity [10], Clarity [11] and standard deviation of Gaussian blur kernel [12] are calculated for nineteen combinations of the haze and background distances used in human visual experiments. Correlation coefficients between the calculated values of measures and the results of paired comparisons are calculated. Experimental results indicate that the measure based on Gaussian blur model provides faithful representation of the perceived blurriness of the transmitted images through the OLED transparent displays.

Acknowledgement

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