An Image-Based Quantitative Metric of See-Through Optical Quality for Displays

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Abstract

This paper proposes an image-based metric to quantify the see-through optical quality of the transparent displays. The experiment included a visual assessment along with the optical metrology for the transparent display. Results revealed that the Complex-Wavelet Structural Similarity index had a high correlation with the perceptual sharpness of see-through images.

Author Keywords

Transparent displays; Micro-LED; Purity; Clarity.

1. Objective and Background

Transparent displays have gained recognition for their wide-ranging applications as next-generation display technologies, including augmented reality systems, heads-up displays and digital signage etc. These displays are based on liquid crystal display (LCD), organic light-emitting diode (OLED), or LED technologies. Transparent LED displays, in particular, stand out for their ability to combine visual clarity with high brightness, making them increasingly popular.

Park et al. have introduced the concept of "purity" to assess transparent display performance under different lighting conditions [1]. The standard IEC TR 62977-2-5:2018 emphasizes the clarity metrics to ensure applicability to transparent display technologies [2]. Kwon et al. (2024) have further explored perceptual-based metrics for display quality, highlighting limitations in traditional measurement methods [3]. Their findings underscore the need for evaluation approaches that align closely with human visual perception, expanding the scope of subjective quality analysis to improve the accuracy of optical measurements across various display applications.

In addition, Tsai et al. utilized the Complex Wavelet SSIM (CW-SSIM) algorithm to evaluate the optical image quality of seams for the transparent tiled Micro-LED displays [4][5]. By using a grayscale guide table as the background, they captured images with a digital camera focused either on the guide table's surface or the transparent display's light-emitting surface. CW-SSIM index was then applied to compare the seam and non-seam areas. Results showed that better seam processing achieved higher CW-SSIM scores, aligning well with human visual observation trends. Although the study did not directly address the image quality of transparent displays in terms of visual transparency, the method demonstrates strong potential as an objective measurement approach for optical transparency quality.

In this study, the authors further investigated the correlations between human visual observations and CW-SSIM index for measuring see-through image quality of the transparent micro-LED displays. Meanwhile, this paper proposes the test method of measuring the optical image quality for transparent displays. This combined approach aims to bridge between subjective human perception and objective metric evaluation, advancing the understanding of display clarity and image quality assessment.

2. Method

This study aimed to evaluate the optical performance and subjective perception of transparent micro-LED displays. The experimental processes were divided into two main parts: the visual assessment and the test method of see-through image capturing with analysis, conducted under controlled conditions to ensure consistency and reliability. All tests were performed in a darkroom environment to minimize external light interference, with ambient illuminance below 5 lx, temperature maintained at 24 ± 3°C, and relative humidity ranging from 25% to 80%. We used an ISO 12233:2000 test chart as the target and a transparent micro-LED to present a set of 24 color full screen patches. Subjects were asked to evaluate the sharpness and clarity of the test chart as viewed through the display. Separately, the see-through images were taken with a digital camera for CW-SSIM index analysis under the same conditions.

2.1. Apparatus

The experimental setup is shown in Figure 1 and Figure 2. The device under test (DUT) in this study is a 15.1" transparent micro-LED display with a resolution of 1366×768×RGB pixels and could display 8 bits for each color channel. A light box was 57 cm wide, 34 cm tall, and 33 cm deep. The light box, internally painted with flat white paint, housed a back light module with a correlated color temperature of 7150 K. The front face of the light box consisted of one opening window of 30 cm × 24 cm. The exterior surfaces were painted white as well. The ISO 12233:2000 test chart is fixedly attached to the center of the inside of the cabinet. The vertical illuminance at the center position of the test chart is 4230 lx. The contrast of black and white of the test chart is around 4.2 %.

Table 1 lists 24 colors that are similar to the XRite ColorChecker® palette with the measures of the DUT's luminance and illuminance at eye position when the light box is turned on.

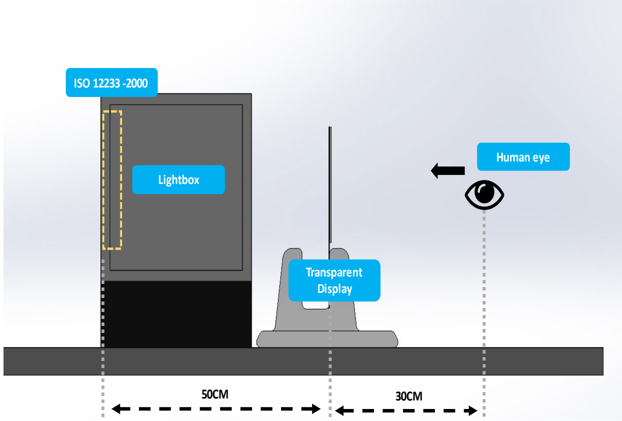


Figure 1. Experimental setup diagram

Figure 2. Experimental scene diagram

Table 1. Testing see-through colors with measures

	Color (R, G, B)	Luminance (cd/m^2)	Illuminance (lx)	No.	Color	luminance (cd/m^2)	Illuminance (lx)
1	(117,82,68)	991.37	271.2	13	(0,0,255)	927.19	221.3
2	(199, 148, 130)	1791.4	788.0	14	(0, 255, 0)	1585.5	653.0
3	(192, 123, 156)	1346.3	512.0	15	(255, 0, 0)	1090.7	342.0
4	(89, 108, 66)	1101	350.0	16	(240, 200, 29)	2145.7	1056.0
5	(131, 129, 175)	1296.5	479.0	17	(193, 84, 148)	1203	417.0
6	(94, 190, 172)	1752.1	791.0	18	(86, 125, 138)	1253.2	448.0
7	(223, 124, 46)	1551.2	677.0	19	(255, 255, 255)	2253.9	1098.0
8	(69, 92, 166)	1058.2	313.0	20	(200, 200, 200)	1872.5	865.0
9	(199, 84, 98)	1330.9	520.0	21	(160,160,160)	1552.4	633.0
10	(92, 60, 103)	932.08	236.2	22	(122, 122, 122)	1283.5	449.0
11	(159, 189, 66)	1933.5	895.0	23	(85, 85, 85)	1038.2	298.0
12	(231, 162, 42)	1886.6	874.0	24	(0, 0, 0)	893.52	207.5

2.2. *Visual Assessment Experiments*

A total of fifteen observers were participated in the psychophysical experiment. The participants with normal or corrected to normal vision were volunteers from National Taiwan University of Science and Technology. The mean age was 26.2 years old, ranging from 23 to 32.

Participants were seated 30 cm away from the transparent display, and the test images were aligned and placed in a light box 50 cm behind the transparent display. During the experiment, the display random sequentially presented 24 colors and insert a black color for the observer rest during each test trial. Participants were instructed to assess these colors as viewed through the transparent display. In addition to evaluating clarity, participants reported the visual indicators on the ISO 12233:2000 test chart, such as sharpness (resolution) number and contrast markers were recorded to assess the transparent display performance.

The evaluation employed two metrics. First, participants rated the clarity of the test chart for each displayed colors about perceived sharpness of visual overall whole picture quality using an 8 category-point clarity scale (1: very bad, 2: bad, 3: poor, 4: mediocre, 5: fair, 6: good, 7: quite good, 8: perfect). Then observers were asked to report the sharpness values for all of four regions of interested (ROI) area on the test chart shown on Figure 3, such as line patterns and resolution grids that were labeled as K1&J1, K2&J2, SW and P1, were used to judge the clarity quality of the see-through display to render fine details and maintain visual consistency.

Each participant repeatedly performed two rounds with 24 colors visual assessments per round. Between rounds, the observer had 5-minute rest period to prevent fatigue and ensure consistent focus. The orders of testing colors were randomized to minimize learning effects and biases.

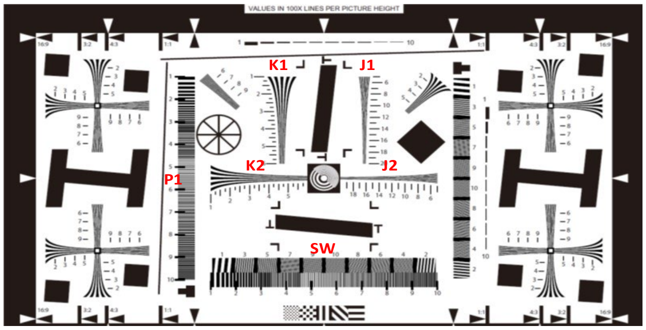


Figure 3. Four regions of interested areas labeled K1&J1, K2&J2, P1 and SW from ISO 12233:2000 test chart

2.3. *Optical Measurement and Image Capturing Setup*

In this study, a digital camera, Canon EOS Mark6D II equipped with EF16-35mm f/2.8L III USM lens, was employed to capture a series of images of the DUT displayed 24 colors under controlled experimental conditions. Corresponding images of the test chart without the display in place were also captured for as the reference image. In order to capture the effective area of the test chart, the camera was fixed distance 30 cm on-axis from the DUT, such that the distance from the camera to the test chart target were 80 cm. The camera's exposure settings were systematically varied during the experiment to ensure a comprehensive evaluation of imaging conditions. The apertures were fixed set at F11 and varied 4 levels of the shutter speeds ranged from 1/15 to 1/125 seconds, covering exposure values (EV) between 11 and 14.

Then the captured images were analyzed using the Complex Wavelet Structural Similarity (CW-SSIM) algorithm, which quantified the structural similarity between the images obtained with and without the transparent display. By comparing the CW-SSIM scores for each of the 24 colors, the analysis provided a precise measure of the display's impact on image clarity and structural integrity.

This study used a spectroradiometer, TOPCON UL1R® to measure the optical and color performance of the transparent display. The spectrophotometer was positioned 100 cm from the transparent display and set the focus on the plane of the test chart. This study used the Konica Minolta T10A® to record the vertical illuminance of 24 colors displayed at the participant's eye position as well. Measurements were performed under two conditions, one was with the light box turned on to provide uniform illumination, and the other was with the background completely blackened using a black velvet cloth with near-zero reflectivity. The measurement results under the light box turned-on condition are presented in Table 1.

3. Results and Discussion

In this paper, we focus on the investigating the test method based on CW-SSIM index of see-through image quality for transparent display. The test method should be practical and simple as well. Nowadays, there are many test patterns and methods for quantified the image sharpness in varied conditions of applications. In the ISO

12233 test chart, there are also many kinds of patterns to assist users to approach their purpose. In order to simplify the proposed test method, the first step is to determinate which pattern is the most suitable for evaluating the see-through image quality.

After the completion of the experiment, the SPSS® statistical software was used to analyze the data collected by the questionnaire. The results of 2-way of Analysis of Variance (ANOVA) revealed that there were two significant main factors affecting perceptual clarity, ROI and luminance (statistical significance level at p-value 0.05) as shown in Table 2. Figure 4 shows a plot of average clarity versus DUT luminance for the four ROI areas. It was also found that observers could perform the best visual assessment for the ROI K1&J1 area than other ROI areas. In addition, a veiling luminance effect was observed. In other words, as the luminance of the transparent display increased, the average clarity value decreased. Therefore, the ROI K1&J1 area is dedicated to CW-SSIM index calculation in the following processes.

Table 2. ANOVA for the perceptual clarity

Source	Sum of Squares	df	Mean Squares	F_0	p-value
ROI (A)	816.615	3	272.205	192.229	.000*
Luminance (B)	1668.947	23	72.563	51.243	.000*
A × B	71.468	69	1.036	.731	.953
Error	3942.267	2784	1.416		
Total	6499.297	2879			

* significance level at p-value < 0.05

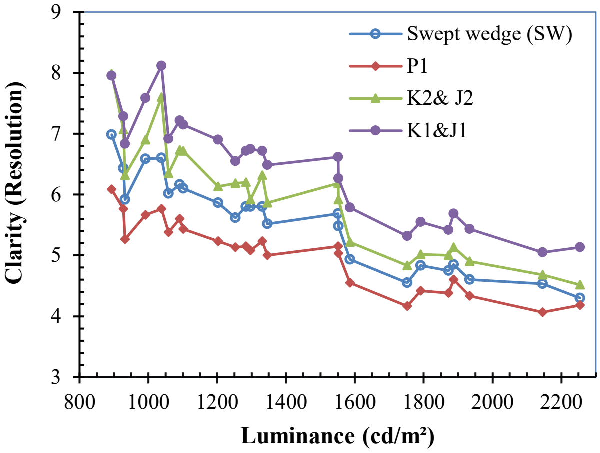


Figure 4. Plot of the average clarity against DUT luminance for 4 ROI areas

3.1. CW-SSIM Index Calculation

To take account the high dynamic range of DUT's brightness, this paper investigated the different exposure times at the fixed aperture setting of F11 were tested to identify the optimal capturing configuration for image clarity and consistency. Figure 5 indicated that the shutter speed setting of 1/125 second provided the most reliable balance between luminance levels and resolution. This setting was subsequently adopted for all subsequent image capture and analysis to ensure consistency and minimize over- or underexposure effects. Some of captured ROI image examples are shown in Figure 6. In next step, we will discuss the results of visual assessments between the overall image quality and local image quality of ROI K&J1. Final the correlations between perceptual see-through image quality and the calculated CW-SSIM index.

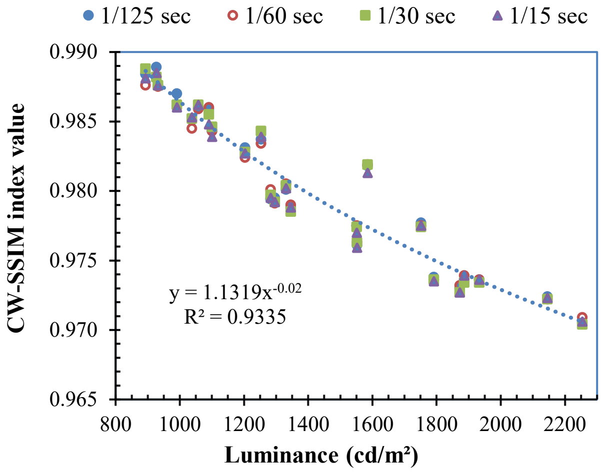
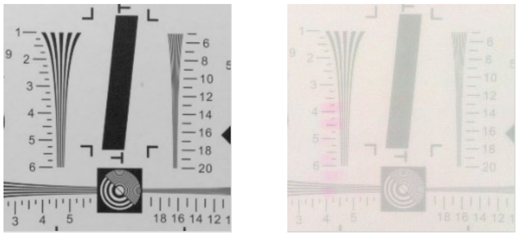
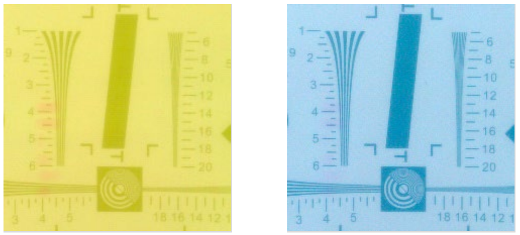


Figure 5. Plot of the CW-SSIM index against luminance for 4 exposure time settings



(a) Reference, without DUT (b) DUT displays white color



(c) DUT displays yellow color (d) DUT displays cyan color

Figure 6. Examples of the captured ROI K1&J1 area

3.2. Consistent Between the Local and Overall Quality

Figure 7 plots the visual assessment results about clarity (sharpness or resolution) of the ROI K1&J1 against the overall image quality for the 24 test colors conditions. The results revealed that the participants responded that the higher sharpness value of the local perceived image on ROI K1&J1, the clearer see-through overall image was experienced. Furthermore, the perceptual sharpness values and the overall see-through image quality score have linear relationship with high correlation, $R^2 = 0.8695$. The results indicated that assessments focused solely on the K1&J1 region could serve as a robust proxy for evaluating the overall image quality of the display. This finding simplifies the evaluation process while maintaining accuracy, offering a streamlined approach to performance assessment for transparent displays.

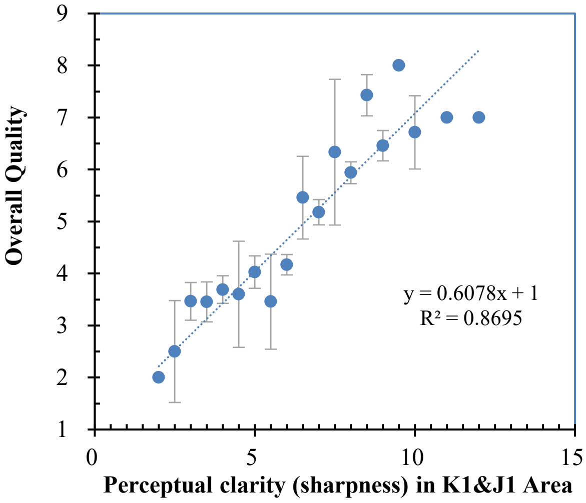


Figure 7. Plot of the average overall quality score against the average perceptual clarity (sharpness) value

3.3. CW-SSIM Index of See-Through Image Quality

Comparing the calculated values of CW-SSIM Index and the average visual assessment score for 24 colors, the results revealed that the higher CW-SSIM index value, the target behind the transparent display could be higher visibility. In other words, there is evidence that CW-SSIM index can be used as one of index for see-through image quality assessment. A regression model is also shown in Figure 8 giving a reasonable high correlation of $R^2 = 0.7674$.

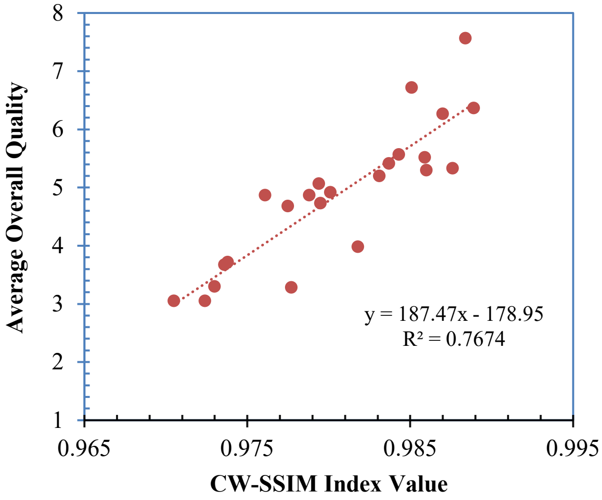


Figure 8. Plot of correlations between the overall quality and CW-SSIM Index

4. Conclusions

A new test method using an image-based quantitative metric was developed to measure the see-through image quality of transparent displays. This study evaluated the optical performance of a transparent micro-LED display, combining subjective evaluations and objective CW-SSIM analysis. The findings revealed that when a transparent display displays different color patches, those with higher vertical illumination will cause visual blur and affect clarity. Additionally, the perceptual clarity of perspective on the ISO 12233 test chart varied by location, with regions of interest K1 and J1 providing the best clarity. This study emphasizes that CW-SSIM index can accurately predict the participants' subjective ratings, validating its reliability as an objective measurement tool. These results highlight the interplay between illuminance, spatial performance, and human perception, providing key insights for optimizing transparent display designs.

5. Impact

This work introduces a practical image-based metric using the CW-SSIM index to objectively evaluate see-through optical quality, bridging the gap between subjective perception and measurable results. Compared to existing methods, it offers higher accuracy and consistency, enabling improved optimization of transparent display technologies like micro-LED and OLED. These findings could influence industry standards and enhance the design of displays for applications.

6. Acknowledgements

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7. References

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