CSD—A New Unified Threshold Metric of Evaluating LCD Viewing Angle by Color Saturation Degradation

Szu-Fen F. Chen, Wei-Chung W. Cheng, and Han-Ping D. Shieh

***Abstract*—Lower luminance contrast ratio and chromatic changes affect the visual performance (i.e. color shift) of a thin-film transistor liquid-crystal device (TFT-LCD) at large viewing angles. The *de facto* method of defining viewing angle, contrast ratio of luminance, fails to represent the substantial visual performance viewed at a larger angle. We found the degradation of color saturation, $dS^*/d\theta$, to be an appropriate metric to aid the conventional viewing angle definition $(CR \geq 10)$. We empirically determined the threshold for defining the color viewing angles of TFT-LCDs, $CVA = \{\theta || dS^*/d\theta| \leq 0.03\}$, which reflects the variation not only in chromaticity but also in luminance. The proposed metric was evaluated by psychophysical experiments, whose results validate the efficacy of the proposed metric.**

***Index Terms*—Color saturation degradation (CSD) metric , contrast ratio metric, just-noticeable difference (JND), liquid-crystal device (LCD) viewing angle evaluation, psychophysical evaluation.**

I. INTRODUCTION

AS THE RAMPING liquid-crystal device TV (LCD-TV) market rapidly replacing the existing CRT TV sets, color performance has become one of the key factors for potential buyers to make their move. Currently, the major challenge of LCD-TV is the visual quality degradation at large angles such as color shift and contrast decrease. Unfortunately, there is no practical and representative metric to describe such quality degradation for the end users. The focus of this paper is to find an ideal metric for evaluating color viewing angle of thin-film transistors LCDs (TFT-LCDs).

In the TFT-LCD industry, the conventional metric, which is used to evaluate the viewing angle of LCDs, is *luminance contrast ratio* (CR), but it is not sufficient to represent the visual performance at large angles, especially color shift. However, the metric (i.e., CR) is simple and easy for judging the LCD's viewing angle performance. In practical applications, we still have not found a new metric with unified threshold to evaluate the color viewing angle as CR did. In academia, the most of academics emphasize to use perfect models for color viewing angle evaluation [1]–[4]. Some metrics were even created by using 3-D models, although, they included both luminance variance and chromatic changes simultaneously. These metrics are not convenient to use in TFT-LCD industry. The new unified threshold metric is necessary to enhance the deficiency of CR for evaluating TFT-LCDs.

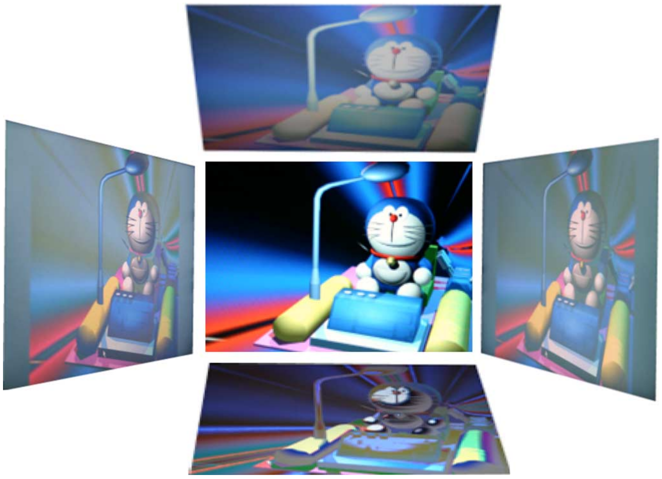

Fig. 1. Visual effects of color shift and contrast degradation at large viewing angles. (Color version available online at http://ieeexplore.ieee.org.)

The variation in CR with viewing angle is a well known phenomenon in TFT-LCDs, adversely affect image, viewing angle, color shift, etc. For color TFT-LCDs, the shift in both chromaticity and luminance can be dramatic with changes in viewing angle. An example is shown as Fig. 1. Conventionally, the viewing angle of a TFT-LCD is determined by a threshold of the contrast ratio of luminance such as

$$VA = \left\{ \theta \left| \frac{L_{\max}(\theta)}{L_{\min}(\theta)} \geq 10 \right. \right\} \quad (1)$$

which indicates the range of viewing angles that the luminance of white $(RGB = \langle 255\,255\,255 \rangle)$ is at least a factor of 10 higher than the luminance of black $(RGB = \langle 0, 0, 0 \rangle)$. This popular metric, however, is not representative of the color performance of a TFT-LCD, because it does not capture the chromatic changes. In practice, when a TFT-LCD is examined at a larger angle, the color shift caused by the retardation value variance of the liquid crystals is more pronounced than the luminance contrast ratio.

We propose a new unified threshold metric, which is particularly suitable for evaluating the visual performance of

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TABLE I
COMMON SPECIFICATION OF THREE TEST PANELS

Item	General Specification	Remark
Module Size (mm)	7 inch WVGA	
Number of Pixels	800 (W) * 480(H)	
Pixel Pitch (mm)	0.1905*0.1905	
Color Pixel Arrangement	RGB vertical strip	
Brightness (cd/m^2)	200 (central)	nominal
Contrast Ratio	300:1	nominal
Color Saturation	50%	nominal
Optimal Viewing Direction	6 o'clock	
Viewing Angle	**By design**	**Due to different types**

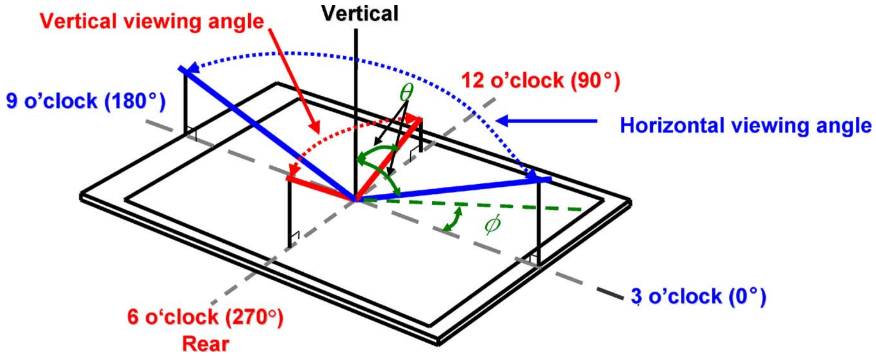


Fig. 2. Viewing angle definition. (Color version available online at http://ieeexplore.ieee.org.)

TFT-LCDs at large viewing angles. Our approach is using the degradation of color saturation to determine the acceptable view angles based on a just-noticeable difference (JND) threshold [6], [7]. We fabricated and thoroughly characterized three TFT-LCDs for analyses, which have very similar structures but perform noticeably differently at larger viewing angles, to verify our proposal. Based on the measured colorimetric data, we derived a numerical metric for viewing angles. We also discuss the other metric, ΔE^*_{uv}, defined by color difference for viewing angles [3], [4], [6], [7]. To evaluate the proposed metric, we used the other three commercial TFT-LCD monitors for experiments, which have completely different designs and characteristics, and conducted psychophysical experiments to collect subjective preferences. The experimental results show that the proposed metric is a mathematically well-defined, representative, reproducible, and objective metric for evaluating the view angles of TFT-LCDs.

II. METHODOLOGY

The methodology of this study includes the following steps: *A*) three types of TFT-LCDs were fabricated as test panels; *B*) the test panels were characterized by using *de facto* test methods; *C*) the measurement data were analyzed to identify the shortcoming of conventional metrics; and *D*) a new metric was proposed.

A. Design of Test Panels

We designed and fabricated three test panels, whose common specification is listed in Table I. For fair comparison, all test panels possess similar optical and electrical properties (e.g. same drivers, same color filters, and same backlight modules), except for their wide-viewing-angle designs. The first panel, TN, is a typical twisted nematic type TFT-LCD panel with super-wide viewing angle films. The rest two are optical compensation bend (OCB) type. One, OCB-90, is OCB-type rubbed in vertical direction. The other, OCB-45, is also OCB-type but rubbed at 45 deg. Despite of their different rubbing directions, the two OCB-type panels have very similar visual performance, which are far superior to the TN panel. This predetermined difference in visual performance will be used to evaluate the efficacy of viewing angle metrics.

B. Photometric and Colorimetric Parameters of Test Panels

We chose the most adopted Swedish Confederation of Professional Employees (TCO) certification [8], [9] for Visual Display Units (VDUs) to characterize the test panels. The TCO certification originated from the end-users' perspective rather than that of the manufacturers. We used the test methods in TCO'03 to measure the optical properties of the three test panels [9]. The standard viewing angle definition is shown in Fig. 2.

By definition, *lightness* is

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16, \quad \left(\frac{Y}{Y_n}\right) > 0.008\,856. \qquad (2)$$

Chroma is defined by

$$C^*_{uv} = \sqrt{\left(u^{*^2} + v^{*^2}\right)}. \qquad (3)$$

Color Saturation (S^*) is defined as the ratio of chroma to lightness

$$S^* = \frac{C^*_{uv}}{L^*}. \qquad (4)$$

In these equations, Y and (x, y) denote the measured luminance and the CIEXYZ chromaticity coordinates of the target color,

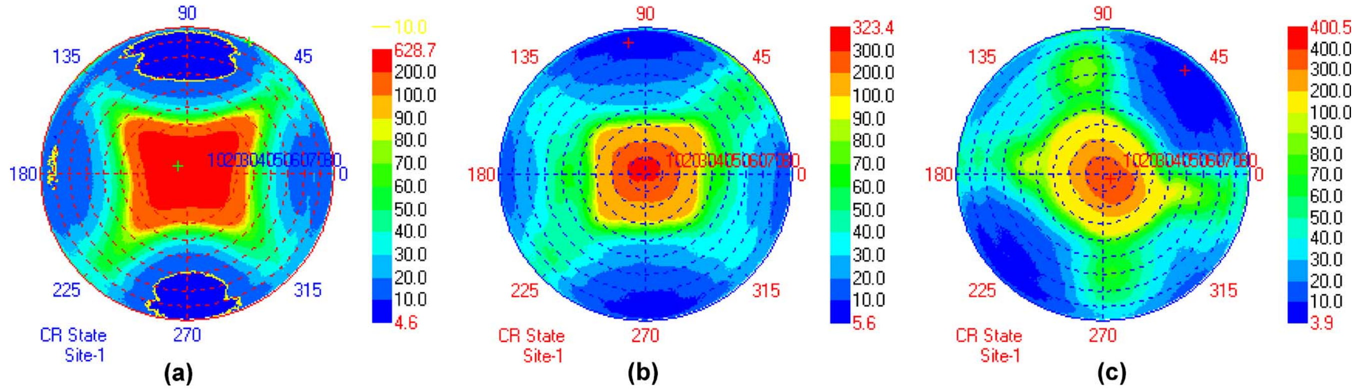


Fig. 3. The iso-contrast contour plots of three 7" TFT-LCDs. (a) TN (b) $OCB-90$, and (c) $OCB-45$. (Color version available online at http://ieeexplore.ieee.org.)

TABLE II
VIEWING ANGLES DEFINED BY LUMINANCE CONTRAST RATIO

Φ	TN		OCB-90		OCB-45	
	$Y_{\theta=0°}$=209.7		$Y_{\theta=0°}$=191.3		$Y_{\theta=0°}$=183.5	
	$Y_{\theta=30°}$	$\theta_{CR=10}$	$Y_{\theta=30°}$	$\theta_{CR=10}$	$Y_{\theta=30°}$	$\theta_{CR=10}$
0°(3 o'clock)	149.22	>85	107.1	>85	109.29	>85
90°(12 o'clock)	86.86	56	85.12	69	125.56	>85
180°(9 o'clock)	129.70	>85	92.02	>85	117.28	>85
270°(6 o'clock)	89.58	55	83.06	71	143.49	>85

respectively. (Y_n, x_n, y_n) denotes the same parameters of the reference white. The reference white was chosen to be $\mathrm{RGB} = \langle 255\,255\,255 \rangle$ measured at normal angle near the center of the panel.

We measured the luminance, contrast ratio, viewing angles and color tri-stimuli (X, Y, Z) every 10 degree. The X, Y, and Z denote the color tri-stimuli defined in the CIEXYZ system [9], [11], [12]. We converted (X, Y, Z) in CIEXYZ to (L^*, u', v', u^*, v^*) in the CIELUV color space [1], [11], [12] and calculated the colorimetric parameters including lightness, chroma, color difference, saturation, etc.

The conventional viewing angles determined by the luminance contrast ratio $CR \geq 10$ are listed in Table II as well as their iso-contrast contour plots in Fig. 3. $Y_{\theta=i}$ denotes the measured luminance at viewing angle $\theta = i$. For example, $Y_{\theta=0}$ indicates normal viewing direction while $Y_{\theta=30}$ indicates horizontal and vertical viewing direction at 30°. From Table II, it is difficult to tell the visual difference between the TN and OCB panels by comparing the horizontal (9 o'clock–3 o'clock) and vertical (12 o'clock –6 o'clock) viewing angles, because the luminance (Y) is angular-dependent. In other words, the Y-value of white-state decreases as the viewing angle increases. In contrast, the Y-value of black-state becomes higher and higher. Consequently, the contrast ratio becomes lower and the color is shifted at large viewing angles as revealed by the iso-contrast contour plots in Fig. 3. These plots convey only the viewing angles defined by contrast ratio in the whole azimuth, but not the visual difference caused by color shift. To sum up, the data may mislead the substantial visual differences between the three panels.

C. Prior Methods for Evaluating Color Viewing Angle

In order to evaluate the color shift, two metrics were proposed in [1], [2]. The first metric used a 3-D model including luminance variance and chromatic change to evaluate the color shift [1]. The metric represents color shift by using a figure of 3-D CIE1931XYZ chromaticity diagram with respect to viewing angles. The second one proposed a metric using the iso-luminance concept to calculate the color difference, defined by CIELAB and CIE1976UCS [6], [11], [12], between two target colors [2]. Both metrics are not suitable for our purpose, but they induce us to evaluate color viewing angle by using color difference.

In TFT-LCD industrial applications, some companies initially attempt to use ΔE^*_{uv} to define the unified threshold metric for evaluating color viewing angles, because the color difference $(\Delta E^*_{\mathrm{uv}})$ is a well-known parameter in colorimetry to describe the variance in luminance and chromaticity simultaneously [3], [4]. First, we used it to characterize the three 7-inch TFT-LCDs.

$$\Delta E^*_{\mathrm{uv}} = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2}. \tag{5}$$

It is necessary to consider luminance and chromaticity simultaneously at large viewing angles [1], [2], [5]. After analyzing the data shown in Fig. 4, we found that we could not distinguish the significant difference between the three panels. The luminance variance was too large and misled the color difference calculation results. In other words, the color shift effect was overshadowed by color difference calculation. In Fig. (4a) and (b), the color differences are almost the same when the viewing angle is smaller than 30 deg and 40 deg, respectively. The ΔE^*_{uv} is about 40 in horizontal direction (9–3 o'clock direction), and is about 60 in vertical direction (12–6 o'clock direction). Even the threshold of the metric is difficult to be decided, especially, when we evaluate a TFT-LCD with different luminance levels. For instance, we compare two TFT-LCD monitors with different luminance levels (e.g. one is 400 $\mathrm{cd/m^2}$ of luminance and the other is 200 $\mathrm{cd/m^2}$). The ΔL^* between different viewing angles of the two LCDs are quite different and result in difficulty for deciding a general threshold of color viewing angle.

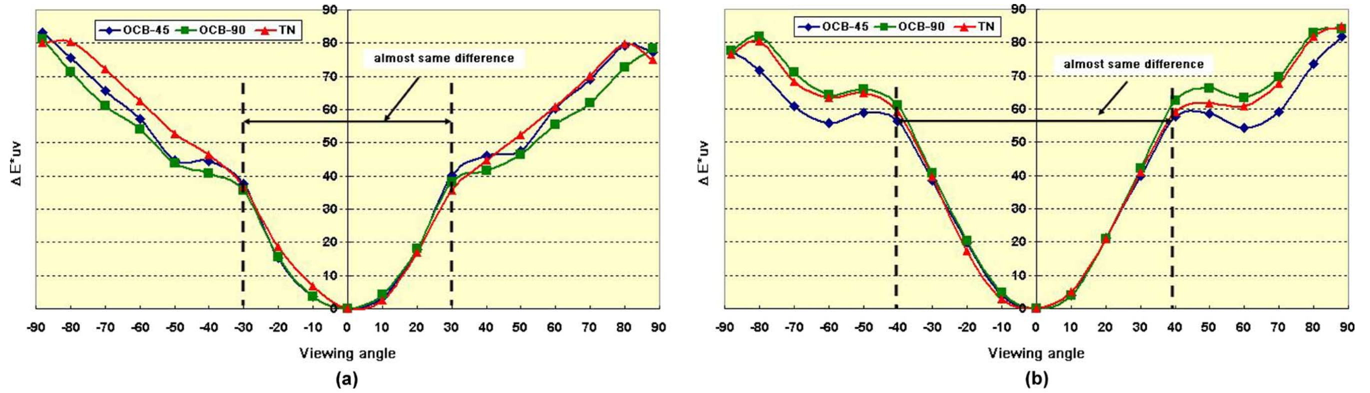


Fig. 4. Color difference (ΔE^*_{uv}) vs. viewing angle in white-state ($\mathrm{RGB} = \langle 255\,255\,255 \rangle$). (a) In horizontal—9–3 o'clock, and (b) in vertical—12–6 o'clock. (Color version available online at http://ieeexplore.ieee.org.)

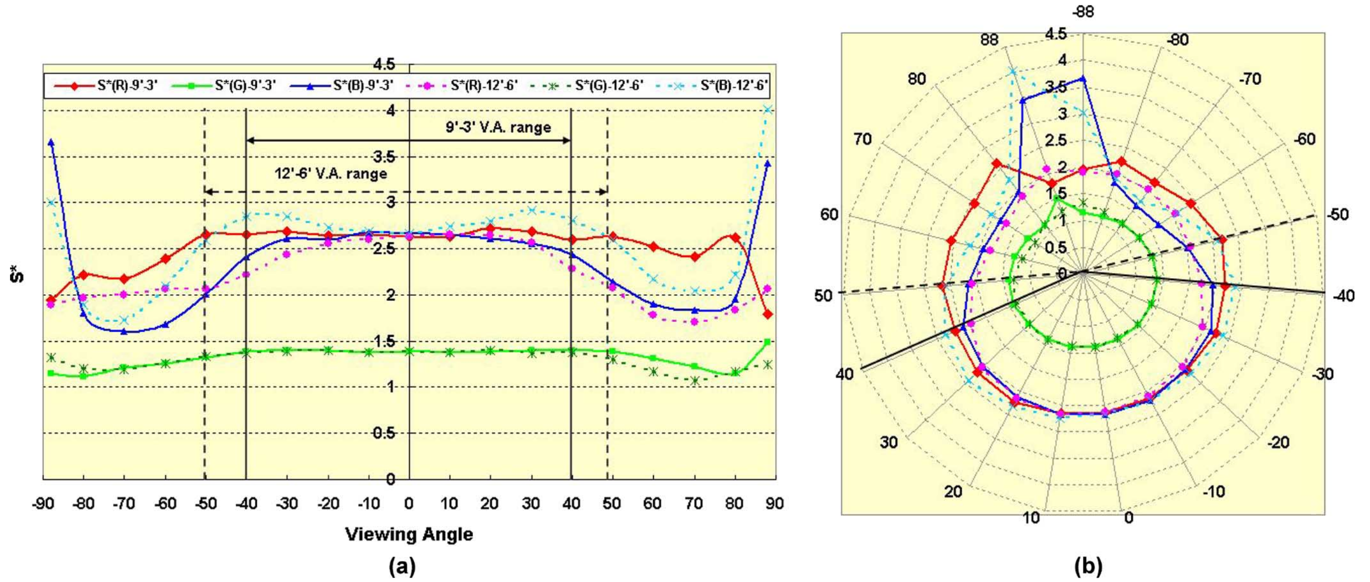


Fig. 5. Measured color saturation vs. viewing angle of TN. (a) Color saturation (S^*) versus viewing angles, and (b) radar diagram of S^* versus viewing angles. Color viewing angle range: 9–3 o'clock: $-40^\circ \sim 40^\circ$ (blue dominates); 12–6 o'clock: $-50^\circ \sim 50^\circ$ (blue dominates). (Color version available online at http://ieeexplore.ieee.org.)

The ΔE^*_{uv} metric, yet, is not suitable to be a unified standard criterion, as luminance contrast ratio $CR \geq 10$, to define viewing angle. The criterion perhaps needs to be changed when evaluating different type TFT-LCDs (e.g. different applications: monitor, notebook or TV). Consequently, to improve the overshadowing effect of L^* in the metric is necessary.

D. Proposed Unified Threshold Metric: CSD

Considering the chromatic changes and luminance degradation effects at large viewings, we propose a new unified threshold metric for defining color viewing angles. The proposed metric employs color saturation degradation in the red, green, and blue channel.

The color saturations of red, green, and blue sub-pixels versus viewing angle of the three panels are shown in Figs. 5, 6 and 7, respectively. In these three panels, the blue and red sub-pixels start to degrade earlier than the green sub-pixels as the viewing angle increases. By setting a threshold on the color saturation degradation, we can find the acceptable viewing angle range. The threshold is defined as the slope of the curve (i.e., derivative of color saturation as a function of viewing angle), and the *Color Saturation Degradation (CSD)* is defined by

$$CSD \equiv |dS^*/d\theta| \leq T. \tag{6}$$

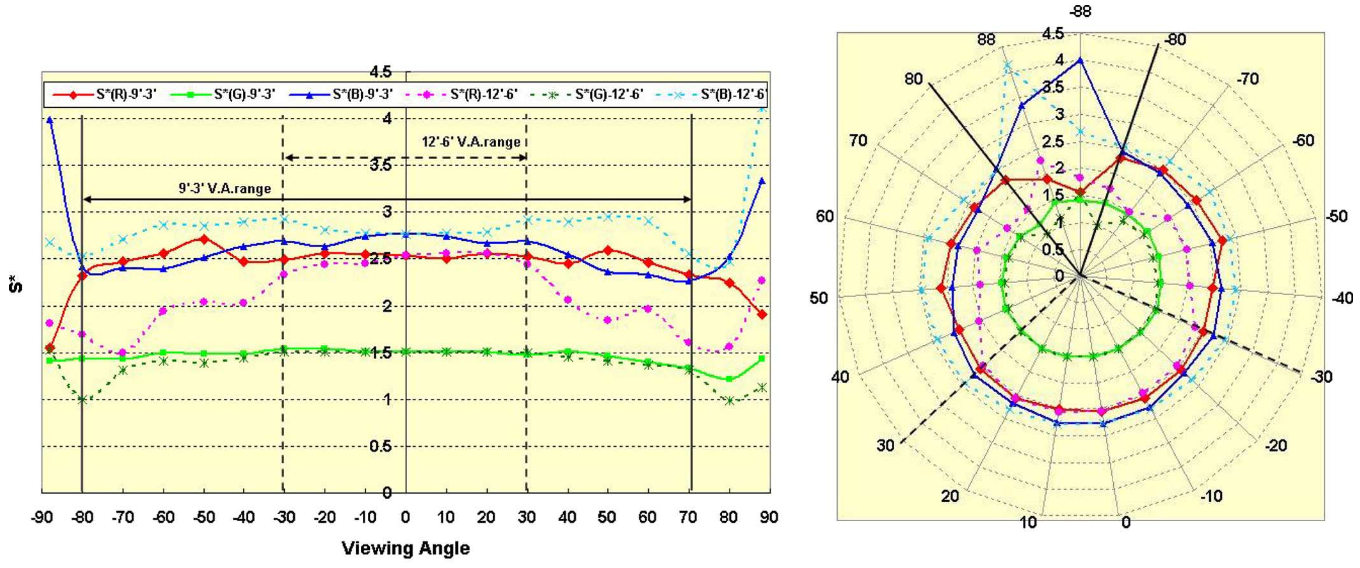
The worst degradation among the three channels determines the *Color Viewing Angle (CVA)*, which is defined as the range of acceptable viewing angles.

$$\begin{aligned} CVA_R &= \left\{\theta : \left|\frac{dS^*_R}{d\theta}\right| \leq T\right\} \\ CVA_G &= \left\{\theta : \left|\frac{dS^*_G}{d\theta}\right| \leq T\right\} \\ CVA_B &= \left\{\theta : \left|\frac{dS^*_B}{d\theta}\right| \leq T\right\}. \end{aligned} \tag{7a}$$

$$CVA = CVA_R \cap CVA_G \cap CVA_B. \tag{7b}$$

According to the empirical JND defined by CIE1976UCS and ISO-endorsed 0.004 [2], [6], [7], the color difference is

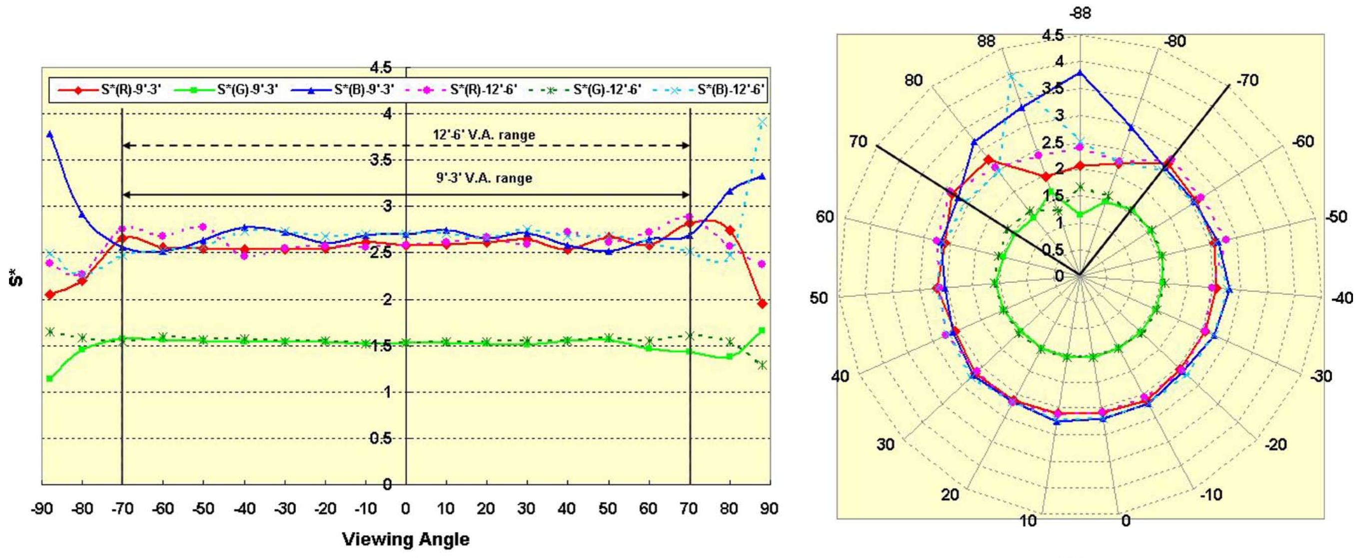
$$\Delta E_{u'v'} = \sqrt{(\Delta u')^2 + (\Delta v')^2}, \quad JND = \frac{\Delta E_{u'v'}}{0.004}. \tag{8}$$



(a)

(b)

Fig. 6. Measured color saturation vs. viewing angle of $OCB-90$. (a) Color saturation (S^*) vs. viewing angles, and (b) radar diagram of S^* vs. viewing angles. Color viewing angle range: 9–3 o'clock : $-80^\circ \sim 70^\circ$ (blue dominates); 12–6 o'clock: $-30^\circ \sim 30^\circ$ (red dominates). (Color version available online at http://ieeexplore.ieee.org.)



(a)

(b)

Fig. 7. Measured color saturation vs. viewing angle of $OCB-45$. (a) Color saturation (S^*) vs. viewing angles, and (b) radar diagram of S^* vs. viewing angles. Color viewing angle range: 9–3 o'clock: $-70^\circ \sim 70^\circ$ (blue dominates); 12–6 o'clock: $-70^\circ \sim 70^\circ$ (blue dominates). (Color version available online at http://ieeexplore.ieee.org.)

We chose the threshold as

$$T = 0.03. \tag{9}$$

The $T = 0.03$ threshold was chosen based on the empirical JND mentioned above. We converted the criteria of CSD into JND, and found that the color difference between the target color and reference white was about 5 JND. In practice, the human eyes can not distinguish the color difference which is smaller than 5 JND. We use the threshold $CSD \leq 0.03$ to define the color viewing angle instead of the conventional viewing angles definition determined by luminance contrast ratio $CR \geq 10$.

From the above-mentioned criteria, we can derive the color viewing angle ranges of the three panels. The color viewing angle ranges of TN derived from Fig. 5 are $-40^\circ \sim 40^\circ$ in 9–3 o'clock direction and $-50^\circ \sim 50^\circ$ in 12–6 o'clock direction. The viewing angle ranges are narrower than the conventional ones defined by $CR > 10$ shown in Table II. The blue channel dominates the color viewing angle at both directions in the TN panel. The results of $OCB-90$ are also shown in Fig. 6. The color viewing angle range of $OCB-90$ is $-80^\circ \sim 70^\circ$ and dominated by the blue channel in 9–3 o'clock direction. In 12–6 o'clock direction, the range is $-30^\circ \sim 30^\circ$ and dominated by the red channel. We observed that the viewing angle range of $OCB-90$ is narrower than that of TN in 12–6 o'clock direction, which is opposite to the results listed in Table II. However, the color viewing angle ranges of $OCB-45$ are almost the largest in the three panels in both directions. The ranges are about $-70^\circ \sim 70^\circ$ in 9–3 and 12–6 o'clock directions and dominated by the blue channel, as shown as Fig. 7.

E. Radar-Diagram Expression of New Metric

In order to let the new metric be a visual tool for users, we also proposed the "radar-diagram" to represent the color saturation in the whole viewing angle ranges from -88° to 88°, which is the maximum capability of measurement equipment. The results are also shown in Figs. 5(b), 6(b), and 7(b). The radar-diagram provides the insight of color saturation uniformity in various viewing angles. A larger radius of the "circle" in radar-diagram indicates the higher color saturation. Thus, the users can perceive the color viewing angle range visually by the shape (roundish or not) of the radar-diagram. Considering the above mentioned with the gamut value (NTSC ratio), we can recognize the visual performance of different LCD modes with similar optical specification easily (e.g. compare various monitors). In the meantime, we can identify which color dominates the viewing angle range by using the radar-diagram as well.

To compare the viewing angle range defined by $CSD \leq 0.03$ shown in Fig. 5 that defined by $CR \geq 10$ in Table II, the substantial visual differences were investigated. Using the conventional viewing angle $(CR \geq 10)$ to evaluate the three panels, their viewing angles are larger than 85 degree in horizontal. The conventional metric lacks the visual differences. The proposed CSD metric can recognize that the $OCB-45$ type is superior to the TN type in terms of color viewing angle. Moreover, the vertical color visual quality of $OCB-90$ is worse than TN, which is opposite to the results in Table II.

III. PSYCHOPHYSICAL EVALUATION

To objectively evaluate the performance of the CSD metric, we applied it to another three TFT-LCDs and conducted psychophysical experiments [10]–[13]. The new metric, justified by psychophysical experiments, is workable and superior to prior metrics in distinguishing the visual difference between TFT-LCDs at large viewing angles.

A. Methodology

We prepared three commercial TFT-LCD monitors, which have different designs for wide viewing angles and vary significantly in color performance. Without revealing information of the monitors, we asked the subjects to judge the color performance subjectively. The subjects' task was to rank the three monitors in order. Then we applied the signal detection theory to analyze the experimental data and obtained a quantitative estimate of color performance of the three monitors, which was compared with the results from the CSD metric.

B. Experiments

The three commercial TFT-LCD monitors were 19$''$ twisted nematic (TN)-type, multi-domain vertical alignment (MVA)-type, and patterned vertical alignment (PVA)-type, which have completely different designs and characteristics. The color performance of MVA- and PVA-type, however, is assumed to be superior to that of TN-type. The monitors were positioned side-by-side at an angle of 30° to the subject, who was 2 m away from the monitors. A standard test pattern consisting of color stripes was used as the target. The 38 subjects were Asian in the age of 22 to 28. Most of them had normal vision after lens correction. The subjects were given enough time to adapt the dark surround while the experimenter explained the task, which was "Please sit still and observe these three monitors from a specific angle; evaluated their color performance and determined their order." The experimenter did not give hints about how to define color performance such that the subject could determine it subjectively.

TABLE III

PSYCHOPHYSICAL DATA OF COMPARING COLOR PERFORMANCE VERSUS VIEWING ANGLE OF THREE MONITORS $(P, Q, R) \equiv R$ SUBJECTS THINK THAT MONITOR P IS SUPERIOR TO MONITOR Q

R (number) = P is superior to Q		***Q***		
		MVA	*PVA*	*TN*
P	*MVA*	-	38	31
	PVA	0	-	25
	TN	7	13	-

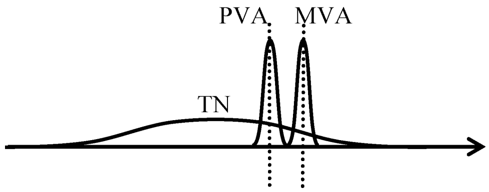


Fig. 8. Color performances as probability distributions.

C. Experimental Results

The subjects' comparison data are shown in Table III, where a number R in the cell (P, Q) means that there are R subjects who think monitor P is better than monitor Q in terms of color performance vs. viewing angle. For example, all 38 subjects agree that monitor MVA is better than monitor PVA, but only 7 consider monitor TN is better than MVA. Notice that "MVA is better than PVA" is a consensus among 38 subjects, but the ranking of TN is undeterminable—25 subjects think"TN is worse than PVA," 6 think "TN is worse than MVA but better than PVA," and 7 think "TN is better than MVA."

D. Data Analysis

According to the *signal detection theory* [10], we can represent the color performance of each monitor as a probability distribution based on the above "votes." The results are shown in Fig. 8. The x-axis represents the color performance. The area under each curve represents the number of votes. All subjects agree that MVA is superior to PVA, so these two distributions, each enclosing 38 votes, are disjoint. The area under TN can be divided into three portions: greater than MVA (7) between MVA and PVA (6), and less than PVA (25). Based on Fig. 8, qualitatively, we can conclude that the visual performance ranking of the three monitors is $MVA > PVA > TN$. In addition, MVA and PVA perform similarly and better than TN, which receives quite diverse opinions.

For comparison, we measured the colorimetric parameters of the three monitors and calculated their CSDs shown in Table IV. The domination CSDs of MVA, PVA, and TN at 30° are 0.0025, 0.0049, and 0.0273, respectively. Intuitively speaking,

TABLE IV
COLOR SATURATION DEGRADATION AT 30° OF THREE MONITORS

ΔS^*@ 30°	***MVA***	***PVA***	***TN***
Red	0.0032	0.0269	**0.8194**
Green	0.0013	0.0018	0.0041
Blue	**0.0750**	**0.1477**	0.1845
Domination CSD	**0.0025**	**0.0049**	**0.0273**

the former two have similar color performance, which is superior to the latter. In other words, the proposed CSD metric is compliant with the psychophysical results.

IV. DISCUSSION

Using CSD to be metric, the visual angular dependence of TFT-LCD is quantified. We can recognize the visual performance of different TFT-LCDs modes with similar optical specifications. The CSD also achieves our objective to improve on the conventional metric by proposing a unified threshold metric and evaluating color shift at large viewing angles. The advantages of CSD are summarized as follows.

1) **Lightness independent**: The degradation of lightness overshadows the color difference calculation, which makes the color shift effect be concealed at large viewing angles. The CSD is independent of lightness and resolves the issue.
2) **Central reference white**: It is necessary to compare the color at large angles with the central white (Y_n, u_n, v_n) of the panel. In other words, the central white shall be the reference white and be employed in the color difference calculations.
3) **Analyze R, G, and B individually**: We have to analyze red, green, and blue individually, because the CVA is determined by the worst degradation among the three channels. By considering the CSD metric and the gamut value, we can recognize the visual performance of different LCD modes with similar optical specification easily.
4) **Provide a visual assistant tool "Radar-Diagram"**: The radar-diagram is a visual evaluation tool for assisting end-users to judge TFT-LCD's color performance. The rounder shape and larger radius of the almost round curve in the radar-diagram imply better chromatic angular uniformity and higher color saturation in TFT-LCDs, respectively.

V. CONCLUSION

We have proposed a new unified threshold metric, CSD, for evaluating color viewing angle of TFT-LCDs by using the degradation of color saturation $(CSD \leq 0.03)$. It is easy to define acceptable color viewing angle ranges by $CSD \leq 0.03$ as conventional viewing angle definition of luminance contrast ratio $(CR \geq 10)$. The threshold of CSD was chosen based on the empirical JND and ISO-endorsed factor 0.004. From the mentioned criteria, we can set the *color viewing angle (CVA)* instead of conventional defined *viewing angle (VA)* to evaluate visual performance of TFT-LCDs at large angles. To combine the new metric with gamut value (the NTSC ratio), we can distinguish the visual performance from different LCD modes with similar optical specification easily. We also proposed the radar-diagram, a visual assistant tool for end-users, to judge the uniformity of color saturation across viewing angles from $-88°$ to $88°$. In order to evaluate the performance of the proposed metric for practical applications, we conducted psychophysical experiments using three commercial TFT-LCDs and the experimental results also validated the efficacy of the CSD metric.

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