Testing performance of CIECAM02 in predicting perceptual contrast

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A psychophysical experiment is performed on two large-size liquid crystal displays under three viewing conditions to assess perceptual contrast. Based on the visual data, the performance of CIECAM02 in predicting perceptual contrast under different viewing conditions is tested and compared with other models by F-test. Results show that the perceptual contrast models in the form of Weber contrast using CIECAM02 brightness Q agreed better with the contrast perception of human visual system compared to the models using luminance, CIELAB lightness L^*, and CIECAM02 lightness J.

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The traditional contrast ratio of display can be calculated as the ratio between the luminance values (in the unit of cd/m^2) of white and black on full screen pattern or some spatial test patterns[1]. These linear formulae of luminance ratio have been adopted by many international standards to qualify the contrast performance of displays. However, they were found to disagree with the human visual system (HVS) in that they cannot explain the nonlinear behavior of HVS[2]. On the other hand, the CIE-recommended color appearance model CIECAM02 has been suggested to calculate the perceptual attributes considering both human perception and ambient conditions[3−6]. Chong *et al.*[5] suggested representing the perceptual contrast of displays using the ratio of CIECAM02 brightness Q of white to black based on physical measurements and theoretical analysis. No visual experiments, however, were involved in their study to verify this. To test the performance of CIECAM02 in predicting perceptual contrast, a psychophysical experiment was carried out on two liquid crystal displays (LCDs) under three viewing conditions in this letter. Based on the visual results, different perceptual contrast models were developed and compared, in which CIECAM02 lightness J and brightness Q[3], CIELAB lightness L^*[7], and luminance in cd/m^2 were employed respectively.

In this letter, the experiment was performed on two 42-inch LCDs with the resolution of 1 920×1 080 (pixels) equipped with in-plane switching (IPS) and vertical alignment (VA) techniques, respectively. The main difference of IPS from VA is that the crystal molecules move parallel to the panel plane instead of perpendicular to it, which may cause their perceptual contrasts to change in different ways with viewing angles or ambient lighting. For visual evaluation, the colorimetric characterization was implemented using the method of localized three dimensional (3D) look-up table[8]. The average characterization accuracy for IPS and VA displays in this experiment was $1.27\Delta E^*_{ab}$ and $1.68\Delta E^*_{ab}$, respectively. Each time before the visual experiment, the display was warmed up for over 1.5 h for stable color presentation. The experimental arrangement is shown in Fig. 1, in which a reference and a test patterns, each including a target surrounded by a ring, are presented respectively on the left and right side randomly determined by the program. The viewing distance from the display to the observer was 1 800 mm. The two patterns were of the same size, i.e., a 4° viewing field for the outer ring and a 2° viewing field for the inner circle (target), and had a separation of 1° in between. For the reference pattern, the target was an approximate D65 white at 340 cd/m^2, which was chosen as the reference white corresponding to $L^* = 100$ and $a^* = b^* = 0$, and the ring was black with RGB = (0, 0, 0). For the test pattern, the ring was also black, but the target was displayed as a set of 19 neutral colors from black to white with corresponding L^* values from 5 to 95 at a step of 5, so that 19 contrast pairs were formed for the test pattern. Outside the two patterns on the screen was 'background' color having an L^* of 50. The CIELAB values of the displayed colors were calculated under CIE 1931 observer and the specified reference white.

A panel of 10 normal color vision observers participated in the experiment, with an average age of 25 years ranging from 23 to 29 years. Every session of the experiment started with a 2-min dark adaptation and a 1-min background adaptation. During the visual session, the test

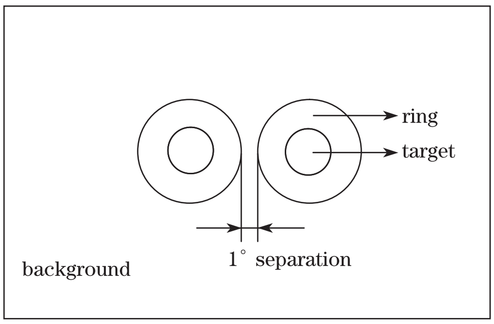

Fig. 1. The experimental arrangement.

pattern and the unchanged reference pattern were shown simultaneously to the observers to evaluate the perceptual contrast of different contrast pairs in the test pattern through the psychophysical method of magnitude estimation[9,10]. The perceptual contrast value of the reference pattern was regarded as 100. In the case that no lightness difference existed between the ring and the target of the test pattern, perceptual contrast would be assigned as zero. Each test contrast pair was judged three times by each observer. The visual assessments were performed on two large LCDs under three viewing conditions: 0°/Dark (0° orientation angle in a dark room), 0°/500 (0° orientation angle under illumination level of 500 lux), and 60°/Dark (60° orientation angle in a dark room). The choice of these conditions was based on the consideration of real viewing situations of large-size LCDs in TV applications. There were a total of 3420 estimations (19 test samples ×3 repetitions ×3 viewing conditions ×2 displays ×10 observers).

As a measure of observer variations and fitting accuracies of models, the Standardized Residual Sum of Squares (STRESS)[9−13] was employed as

$$\mathrm{STRESS} = 100\sqrt{\frac{\sum (x_i - f\cdot y_i)^2}{\sum x_i^2}}, \tag{1}$$

where $f = \frac{\sum x_i y_i}{\sum y_i^2}$, x_i and y_i are two data sets to be compared. For a perfect agreement between two data sets, STRESS will be zero. A higher STRESS value indicates poorer agreement between the two variables.

Table 1 lists the observer variations in terms of STRESS. The average STRESS values were 13.3 and 18.1 for the intra- and inter-observer variations, respectively, which set a base line for testing the performance of models.

To test the performance of CIECAM02 in predicting perceptual contrast, the contrast models employing perceptual attributes were constructed here in the form of Weber contrast[14], shown as

$$C = a_{\mathrm{sf}}\cdot(I_{\mathrm{t}} - I_{\mathrm{r}})/I_{\mathrm{r}} = a_{\mathrm{sf}}\cdot(I_{\mathrm{t}}/I_{\mathrm{r}} - 1), \tag{2}$$

where a_{sf} is a scale factor fitted by visual data, and I_{t} and I_{r} represent perceptual attributes for the target and the ring, respectively. In addition, the luminances in cd/m^2 were used as I_{t} and I_{r} for comparison. The corresponding models adopting CIECAM02 J and Q, CIELAB L^*, and luminance values as I_{t} and I_{r} were named the models of PCJ, PCQ, PCLg, and PCLu, respectively.

Based on the visual results of all observers, the performance of these four models were tested.

Firstly, taking the values of luminance, L^*, J, or Q measured under each viewing condition as the input data of I_{t} and I_{r}, different models were fitted with the visual contrasts of 19 contrast pairs under the corresponding viewing condition, which resulted in the scale factors as given in Table 2.

Next, the performance of the models using different color attributes is illustrated in Fig. 2, where the visual contrast values are plotted against the predicted contrast data by different models under each viewing condition for the IPS and VA displays, respectively. As seen from Fig. 2, the visual contrast changed little from the conditions of 0°/Dark to 0°/500, whereas they varied obviously from 0°/Dark to 60°/Dark for both displays. These results indicate that the 60° viewing angle had more influence on perceptual contrast than the 500-lux ambient lighting. A difference also existed between the visual contrasts of the IPS and VA displays under 60°/Dark, i.e., a decline at high contrast level for IPS display and an increase at low contrast level for VA display compared with those under 0°/Dark. This difference is due to their different viewing angle characteristics. Despite these differences, for all the six viewing conditions of the two displays, the plotted points of PCQ were more convergent to the 45° lines than the other models, which implied that the PCQ model agreed best with the visual results of contrast.

The prediction accuracies of different contrast models were also calculated in terms of STRESS between the predicted contrasts and the corresponding visual data, as listed in Table 3. All models except PCLu gave reasonable predictions, i.e., they performed better than the inter-observer variability of 18.1. The model PCQ

Table 1. Intra- and Inter-observer Variations in STRESS

LCD	IPS			VA			Mean
Viewing Condition	0°/ Dark	0°/ 500	60°/ Dark	0°/ Dark	0°/ 500	60°/ Dark	
Intra-variation	15.1	13.1	12.4	13.6	12.6	13.0	13.3
Inter-variation	18.4	17.6	19.4	17.2	18.7	17.5	18.1

Table 2. Scale Factor a_{sf} of the Models using Different Color Attributes

Display	View Condition	PCLu	PCLg	PCJ	PCQ
IPS	0°/Dark	0.133	0.878	3.884	19.360
	0°/ 500	0.443	2.976	4.517	20.878
	60°/Dark	0.344	2.203	6.260	25.497
VA	0°/Dark	0.084	0.572	2.963	15.619
	0°/500	0.258	1.770	3.331	17.163
	60°/Dark	0.351	2.301	4.913	21.803

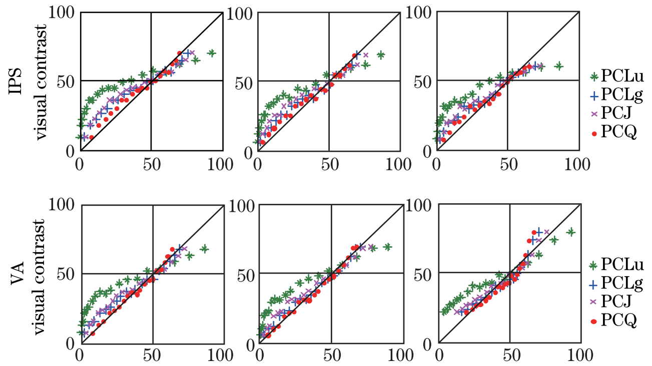

Fig. 2. Visual contrasts vs. predicted contrasts of different perceptual contrast models under different viewing conditions. Also shown are 45° lines.

achieved the smallest STRESS values for each case with different displays and viewing conditions, and also the least average value of 7.8 ranging from 5.1 to 10.4, followed by PCLg and PCJ. In comparison, PCLu had the largest STRESS values with the average of 37.8 ranging from 27.3 to 44.3.

Using squared STRESS, the F-test can be applied to test the statistical significance of the difference between the two models[9]. The F value of data set A to B is given as

$$F = \frac{\mathrm{STRESS}_\mathrm{A}^2}{\mathrm{STRESS}_\mathrm{B}^2}. \tag{3}$$

The F-test results are summarized in Table 4 using the mean STRESS values from Table 3. The model PCQ clearly outperformed PCJ significantly, and also gave better performance than PCLg, though the difference between PCLg and PCQ was insignificant. In comparison, PCLu performed significantly worst among all models.

In summary, the models using perceptual attributes outperformed model PCLu of luminance. Among the three models employing different perceptual attributes, L^*, J, and Q, the CIECAM02 brightness-based PCQ model agreed best with the nonlinear behavior of HVS for different contrast pairs under every viewing condition.

Owing to the satisfactory performance of CIECAM02 brightness Q in predicting contrast, a normalized generic perceptual contrast model of Q is given as

$$PCQ_\mathrm{n} = a_{\mathrm{sf\_n}} \cdot (Q_{\max}/Q_{\min} - 1), \tag{4}$$

where $Q_{\max}$ and $Q_{\min}$ are the brightness values of CIECAM02 for the brightest and darkest part of the test pattern, respectively; and the normalization factor $a_{\mathrm{sf\_n}}$ is defined as

$$a_{\mathrm{sf\_n}} = 100/[(Q_{\mathrm{maxRef}}/Q_{\mathrm{minRef}}) - 1], \tag{5}$$

Table 3. Performance of Different Models in STRESS

Display	View Condition	PCLu	PCLg	PCJ	PCQ
IPS	0°/Dark	44.3	17.0	20.5	7.9
	0°/ 500	38.2	12.0	20.2	8.7
	60°/Dark	42.9	15.8	20.0	9.5
VA	0°/Dark	39.4	11.7	14.7	5.1
	0°/ 500	34.8	7.7	15.2	5.4
	60°/Dark	27.3	9.3	10.9	10.4
Mean*	/	37.8	12.3	16.9	7.8

*The smallest value of the mean STRESS is printed in bold font, while the largest is underlined.

Table 4. F-test Results of Different Models (α=0.05, F_C = 0.39, 1/F_C = 2.60)*

	PCLu	PCLg	PCJ	PCQ
PCLu	/	0.10	0.20	0.04
PCLg	9.53	/	1.91	0.41
PCJ	5.00	0.52	/	0.21
PCQ	23.31	2.45	4.66	/

*The values for significant differences between the two models located in the corresponding rows and columns are in bold italic font.

where Q_{maxRef} and Q_{minRef} are the brightness values of CIECAM02 for the reference pattern under the same viewing condition as the test pattern. Hereby, the $\mathrm{PCQ_n}$ value in this study for the reference pattern, which had the maximum contrast, was equal to 100.

This generic model $\mathrm{PCQ_n}$ is a relative model which predicts the perceptual contrast of the test pattern relative to that of the reference under the same viewing condition. However, the perceptual contrast values of the reference pattern under different viewing conditions may be perceived differently due to the impact of viewing conditions. Therefore, further study is necessary to consider these effects of viewing conditions and to develop an adaptive model by presenting the referece pattern under a fixed viewing condition while the test patterns under different viewing conditions.

In conclusion, based on the visual results, the prediction performance of different contrast models employing luminance in cd/m^2, CIELAB L^*, and CIECAM02 J and Q are tested and compared. The perceptual attributes, especially the CIECAM02 brightness Q, is found to work much better in predicting perceptual contrast than luminance. Finally, a normalized generic perceptual contrast model of Q, namely, $\mathrm{PCQ_n}$, is developed due to its satisfactory performance in predicting perceptual contrast.

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