Subjective Evaluation on Printed Paper for Reflective LCD

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Abstract

Subjective evaluation on printed paper was carried out in order to fix important specifications for the reflective LCD, with emphasis on the luminous reflectance and contrast ratio of monochromatically printed paper. As a result, an important parameter *P* was extracted and found to express the visibility of the reflective LCD. The definition of the parameter *P* is given and the usefulness of the *P* will be discussed in connection with the visibility. Using this parameter, the intuitive visibility was expressed as a qualitative function of brightness and contrast ratio. And the way to be followed in the development of the reflective LCD was identified.

1. Introduction

Display performance specifications are given by many parameters such as brightness, contrast ratio,[1] resolution, color purity and so on. These specifications have been helpful to characterize the displays such as CRT (cathode ray tube) of the emissive type and LCD (liquid crystal display) of the transmission type. On the other hand, the development of the reflective color LCD has encountered with the conflicting relations among the specifications mentioned above.

Brightness of the reflective LCD depends on not only illumination conditions of ambient lights but also reflectivity of the device. Ambient lights are not well-defined in comparison with the backlight in the transmissive LCD. The reflectivity of the reflective LCD is determined by aperture ratio, reflectance of the reflectors, transmittance of the polarization film and the color filter, and performance of an electro-optic effect of the liquid crystal layer.[2] At present, improvement of the aperture ratio is so high that more than a few percentages of the current brightness can not be increased. There is a way to increase brightness using the reflectors with gain factor at the sacrifice of viewing angles. This gain reflector is able to increase brightness without increase or decrease in the contrast ratio. The employment of the color filter of the absorption type at the lower concentration of the pigments is helpful to increase brightness. However, it will not give higher contrast or better color purity in the display. The higher transmission of the polarization film in the reflective LCD results in the brighter image quality with poor contrast ratio. There is a well-known trade–off relation between brightness and contrast ratio for the reflective LCD using guest host LC modes.

In these situations, it is evident that there exists no full-color reflective LCD. Important specifications for the reflective LCD do not seem to be identified yet. Therefore, in this paper we carried out subjective evaluation on printed paper in order to determine important specifications for the reflective LCD, with emphasis on the luminous reflectance and contrast ratio of printed paper.

2. Experimental

A set of printed paper was prepared with the different values of luminous reflectance and contrast to mimic the screen image of reflective LCD, using a printing machine (Fuji Photo Film, Co., Pictro Graphy 3000). The luminous reflectance of each sample was measured with a spectrophotometer (Minolta, Co., CM-3700d), in which the sample to be measured was placed under diffusive illumination and the spectrum was detected and measured at 8 degrees from the surface normal under the condition of no specular reflection components.

There were 16 sheets of printed paper, comprising of the brightness of 60%, 40%, 30%, and 20%, and the contrast ratio of 20, 15, 10, and 5, respectively. The brightness is corresponding to the brightest part of the test image, the value was normalized using a white standard as 100% reflectance. And the contrast ratio is defined as the luminous reflectance ratio of the brightest part to the darkest. The brightness of the dark part for each test sheet is summarized in the Table 1. These values are consistent with those measured by the above spectrophotometer.

The image content thus prepared is shown in Fig. 1, which is a multi-window desk top image. The printing machine produced 16 sheets of photography with a glossy finish, which are the same size of diagonal 9.6 inches with 1024×768 dots (the resolution of 133 dots per inch).

Table 1. Reflectance of the Dark Parts in the 16 Samples

Brightness \ Contrast	20	15	10	5
60%	3%	4%	6%	12%
40%	2%	2.7%	4%	8%
30%	1.5%	2%	3%	6%
20%	1%	1.3%	2%	4%

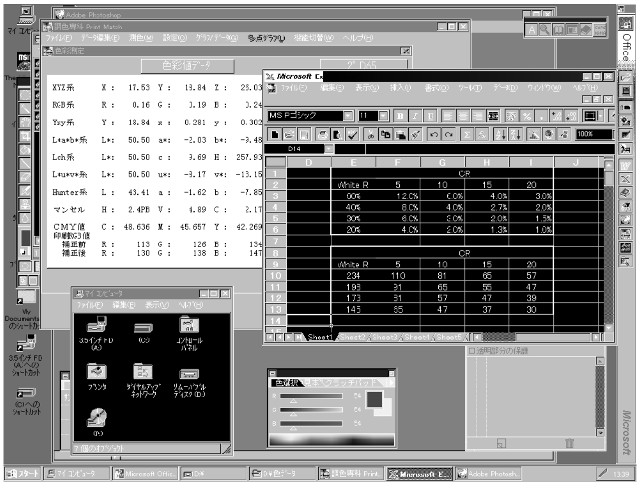

Figure 1. Image of present test samples.

These samples mentioned above were requested to be placed in the order according to the visibility. There were 20 people who joined in subjective evaluation of the ordering work at the desk in office illuminant environments. If there happened to him or her that the samples look the same, then these samples are counted in the same order of the visibility.

3. Results and Discussion

The visibility was expressed as the numerical value, making a point for the best visibility as one, for the second as two, …, for the last as 16, respectively. The average points for each sample were summarized in the Table 2.

Table 2. Average Points for the 16 Samples

Contrast / Brightness	20	15	10	5
60%	1.15	2.20	4.50	12.10
40%	3.45	4.50	6.70	13.00
30%	6.10	7.60	10.45	14.15
20%	10.40	10.10	12.00	14.75

The above subjective results suggest the followings,

1) The high visibility is given to the samples with both high brightness and high contrast.
2) Four worst visibility samples are occupied by the samples with the lowest contrast of 5.
3) There are the almost same visibility samples with the different brightness and contrast.

To make a numerical discussion on the visibility, the following equation was introduced,

$$P = 116((Yw/100)^{1/3} - (Yk/100)^{1/3}), \quad (1)$$

where Yw and Yk are corresponding to the luminous reflectance of the bright and dark parts of the sample sheets, respectively. Thus, the *P* is equivalent to the difference in the lightness of the bright and dark parts. The calculated *P* values are summarized in Table 3.

The capital letter in Table 3 at the intersection of contrast column and brightness row corresponds to the sample with the specific *P* value. The capital A is the sample of the highest value. The capital P corresponds to the lowest one. Relation of the average point in Table 2 and the *P* value in Table 3 is shown in Fig. 2.

Table 3. The *P* Values for the 16 Samples

Contrast / Brightness	20	15	10	5
60%	61.8/A	58.2/B	52.4/D	40.6/K
40%	54.0/C	50.8/E	45.8/H	35.5/N
30%	49.0/F	46.2/G	41.6/I	32.2/O
20%	42.8/J	40.3/L	36.3/M	28.2/P

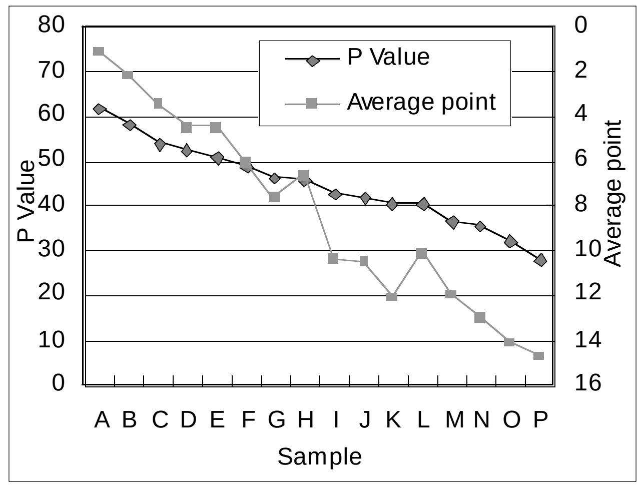

Figure 2. Correlation between P value and average point

There was found a strong correlation between the subjective evaluation in Table 2 and the *P* values in Table 3. Therefore, the *P* value seems a good parameter to specify the display quality of the reflective LCD. The second result mentioned above suggests us that the *P* values with larger than 40 are favorably visible. This means that the samples with the contrast of more than 10 and with the brightness of more than 30% are good enough to be employed as reflective LCDs. In connection with this finding it is worth to be noted here that the reflective color LCD panels with brightness of 30% and contrast of 10 were developed recently.[3]

In the next the visibility is expressed as a function of the Yw and Yk in Fig. 3. The region at the upper right corner is the most favorable. On the other hand, the region at the lower left one is worst. This contour plot of the parameter *P* shows that the favorable region is expressed as a small region while the unfavorable region is exaggerated in the coordinates of Yw and Yk. This situation is due to the functional form for *P*, which gives high values at high Yw and low Yk.

It is familiar for panel makers to use brightness and contrast ratio instead of Yw and Yk. Here the brightness is defined as Yw and the ratio as Yw/Yk. In Fig. 4 the contour of *P* is plotted as a function of Yw and Yw/Yk. The less interested region with low luminous reflections and low contrast ratios is squeezed at the lower left corner.

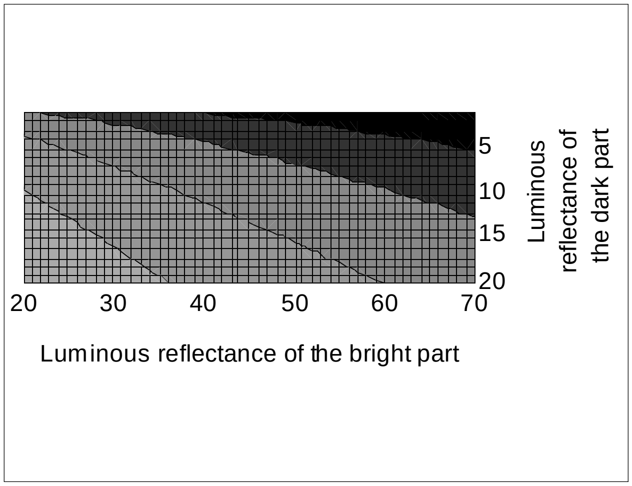

Figure 3. Contour plot of P as a function of Yw and Yk

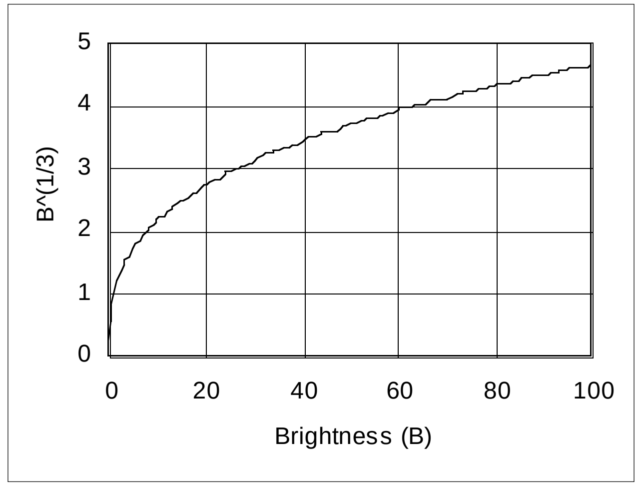

Figure 5. Contribution factor of brightness

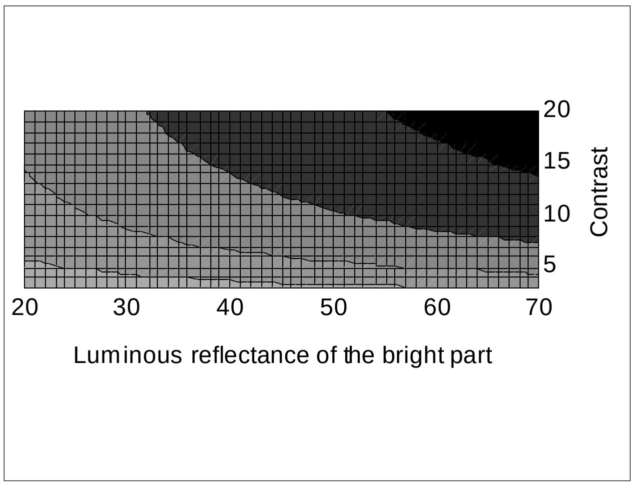

Figure 4. Contour plot of P as a function of Yw and Yw/Yk

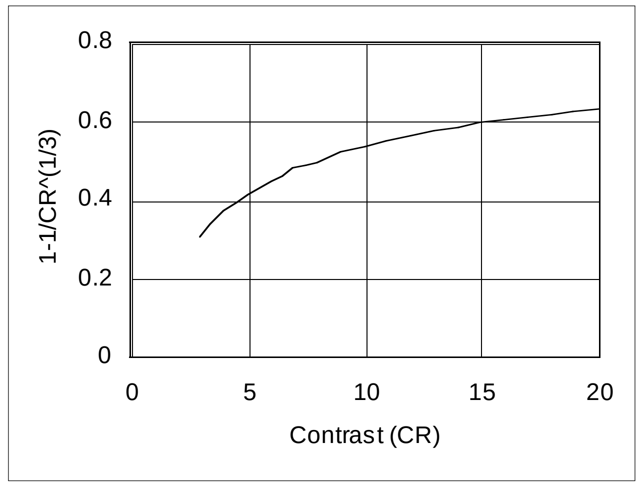

Figure 6. Contribution factor of contrast ratio

The restructured form of *P* is formulated as follows,

$$P=(116/100^{1/3})\, B^{1/3}(1 - 1/CR^{1/3}),$$

$$B=Yw \text{ and } CR=Yw/Yk. \qquad (2)$$

The above equation is discussed in detail. The parameter *P* is governed by two factors. One of them is the brightness B. The brightness contributes to the *P* value with dependence of $B^{1/3}$. This factor is depicted in Fig. 5. There is rapid contribution to the *P* at the small B values and this factor shows small increment in the *P* value at the large B values.

The maximum value of the B is limited to the value of 100%, which corresponds to the brightness of the white standard reflector.

Another factor responsible for the magnitude of the *P* value is contrast ratio, CR. The contribution of CR to the *P* value is not as simple as that of brightness. The factor due to CR is shown in Fig. 6.

Figure 6 shows that there is not a considerably increased contribution at the high CR of 15 to 20. On the other hand, there is 29% increase in the *P* value if the contrast ratio increases from 5 to 10.

The *P* value of reflective LCD is an experimental quantity measurable with a spectrophotometer. The visibility is a matter of subjective evaluation. The numerical value of the visibility is relative. There is intuitive response of users or evaluators to decide which printed paper is favorably visible. If there should be a single parameter to be extracted from various specifications on the reflective panels, it would be a parameter *P*. The evaluation of the visibility is given by the artificially numerical value in this paper. The distribution and frequency is summarized in Fig. 7, where the 16 samples from A to P are arranged in the order of the visibility. At the high evaluation points the distribution is sharp and the frequency is high. On the other hand, the frequency is low and the distribution is wide at the low evaluation points or the low *P* values.

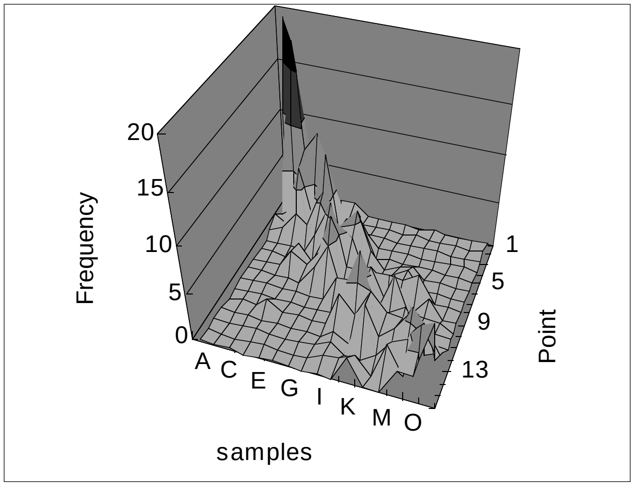

Figure 7. The frequency and distribution of the evaluation point

In 1997 the guest host LCD with the brightness of 30% and the contrast ratio of 5 was developed.[4] In 1998 the single polarizer LCD with the brightness of 30% and the contrast ratio of 10 was developed. The later panel is now commercially available. The *P* values of these panels are given as follows:

$$P\ (\text{GH-LCD}) = 32.3,$$

$$P\ (\text{SP-LCD}) = 41.6.$$

According to the present subjective evaluation, the *P* value of less than 40 is unfavorably visible. Thus, as far as the guest host LCD technology concerns, the increase of contrast ratio is the direction to be implemented. The target specifications of the next generation reflective LCDs seem to be the brightness of more than 40% and the contrast ratio of more than 15, which gives the *P* values of more than 50.8.

The above subjective evaluation leads to a conclusion that the reflective LCD have to show large difference in the lightness of the bright and dark parts in the display panels for the better visibility. The color purity and color reproduction of the reflective LCD are another important specifications. These are beyond the present scope.

4. Conclusions

There was a trade-off relation between brightness and contrast for the reflective display, and the parameter *P* was found a good parameter for the visibility of the reflective LCD. We are able to express the visibility a qualitative function of brightness and contrast. We identified the way to be followed in the development of the reflective LCD.

5. Acknowledgment

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6. References

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