The Influence of Coloured Backgrounds on Mura Detection in TFT-LCDs

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Abstract

'Mura' is a type of defect caused by irregular luminosity variation in liquid crystal displays. It is currently inspected and graded against neutral grey backgrounds in factories by well-trained human assessors. The aim of this research is to provide more reliable grading results from experts in agreement with ordinary observers watching real complex images on LCDs. This work is a pilot study. Since colour is one of the essential elements of complex images, we initially chose to focus on the influence of uniform coloured backgrounds on Mura detection. Analysis of the results shows that both CIELAB and CIEDE2000 colour-difference formulae are useful tools in establishing just-noticeable difference (JND) criteria for Mura grading tasks. The small correlation coefficients between the predicted and visual results, however, imply better experimental techniques should be applied in the future study. The new experiments will be conducted to take into account the spatial backgrounds.

Introduction

The use of the term "Mura" in the TFT-LCD industry originated in Japan and has been widely adopted by the display industry. This term is used to represent almost all irregular luminosity variation defects in liquid crystal displays. An exaggerated image of the Mura defect is shown in Figure 1. These kinds of defects usually occur when the processes of photolithography, polyimide-rubbing, or cell assembly are unstable or contaminated by small particles. They form in various shapes and cause slight changes in the transmission property in local areas of the display [1]. In addition, the non-uniformity caused by back light and thin film materials such as polarizers, diffusers and brightness enhancement films will also induce Mura defects. To some extent, Mura defects may not only affect image quality but could also mislead diagnoses in medical applications. Due to its intangible shape and size, low contrast and brightness characteristics [2], Mura defects are really difficult to detect using ordinary measurement instruments. Thus, during the past ten years, industrial and academic communities around the world have sought to establish a reliable automatic inspection system [1, 3-5] as well as a widely-accepted inspection standard [2,6]. Compared with the automatic detection, however, the influence of Mura on image quality is much more complex because it involves much advanced knowledge of vision science; in addition the definition of image quality is vague and abstract. Therefore, to date, there has been very limited research aimed at the influence of the Mura defects on (complex) image quality.

Many studies on Mura detection have been performed previously. Although different approaches were used, many of them were conducted primarily using knowledge of human vision science, particularly the contrast sensitivity [8-10]. When the luminance of background is lower than 10 cd/m^2, its influence on the detection of thin-line Mura and small-dot Mura appears significantly due to the decrease in contrast sensitivity function (CSF) under dim viewing conditions. Furthermore, the contrast detection threshold of the Mura patterns decreases with display luminance [11,12]. If, however, emphasis is put on the characteristics of the Mura itself, visibility is greatly influenced by the spatial gradient of luminance rather than the deviation in luminance [13]. In a recent study [14], the size of Mura was again proven to be the major factor on contrast threshold; however the influences of position and background colour were previously overlooked but now come into play. In that study, a red background was reported to have the greatest visual contrast threshold, followed by green and blue backgrounds. On the other hand, the influence of coloured backgrounds on Mura detection can also gain support from research in vision science. Owens [15] concluded that the sensitivity of the luminance channel is less for chromatic stimuli than for achromatic ones.

Figure 1. *A typical sample of Mura defect [7]*

Colour is an essential element of complex images (a complex image, in some way, can be simply treated as a combination of different colour patterns with different intensities and frequencies [16]). For this reason, this study is focused on the effect of uniform coloured backgrounds. Unlike other studies, the analysis was conducted from the perspective of a uniform colour space, with the intention to establish a model to predict the influence of colours in Mura detection tasks.

Method

Equipment

A 22-inch EIZO CG220 LCD was used as the experimental platform in this research. Before starting the experiment, the relevant characteristics of this high-end display were evaluated. Spatial uniformity and stability are particularly essential to this research, as all experiments rely on a consistent uniform background. An ideal uniform background provides a good reference for experimental stimuli and has less influence on the assessment.

Spatial Uniformity

To investigate the spatial uniformity of the EIZO CG220 display, a full-screen white background was divided up into a 5x7 grid and each cell was sampled using a Minota CS-1000 tele-spectroradiometer (TSR). Figure 2 is a schematic diagram to illustrate the sample arrangement for testing spatial uniformity. The TSR was positioned 1m away from the display at the average height of observers' eyes during the visual assessment. The physical layout of this measurement was set to match the real experimental conditions. Unlike the regular spatial uniformity measurement carried out in production lines of LCD factories, the optical axis of the TSR's lens was initially perpendicular to the display centre and then tilted to each measurement point over the entire screen as the measurement went on. This setup provides a realistic mimic of eye movement through the entire screen when observers try to find subtle non-uniform patterns by scanning the display.

The measurement data were transformed into CIELAB units under CIE 1931 standard colorimetric observer and the variation in colour differences was then calculated between each individual position and the centre position. Table 1 and Figure 3 show the results and colour-difference distributions, respectively. As it can be seen that the results (with a mean of 2.19 ΔE^*_{ab}) are large compared with normal luminance variation for Mura, the simulated Mura patterns were fixed in the centre of the display in order not to confuse observers during their visual assessments.

Table 1 Spatial Uniformity (ΔE^*_{ab}) relative to the centre

2.16	2.24	2.76	2.29	2.05	2.47	2.46
3.15	2.12	1.71	1.36	1.20	1.91	2.75
3.23	1.58	0.76	0.00	0.44	1.52	2.66
3.63	2.46	1.16	1.00	1.36	2.20	3.29
4.12	2.94	2.38	1.99	2.72	3.05	3.58

Temporal Stability

It is a common sense that all displays require a minimum period for the electronics to warm up and deliver consistent colours. In the LCD industry, 30 minutes is a typical minimum requirement for this stabilisation time; however, sometimes it takes longer for specific and critical measurements.

Figure 4 shows a set of stability measurement results from an internal evaluation report [17] for this display. According to the chart, 2 hours is recommended as warm up time. While 10% of measurement error is the minimum requirement for engineering measurements, the white luminance variation (3.9%) of the display is relatively low.

Tone Reproduction

To understand the behaviour of a display, it is sensible to start with tone reproduction. While perfect additivity of colour channels is not usually the case for LCDs, tone reproduction can help to understand how good or bad their additivity is. Moreover, it can also help built up a characterisation model which provides a reasonable prediction between input and output signals. Figure 5 depicts the measurement of tone reproduction for the display. Digital signals ranging from 0 to 255 were measured for each colour channel. Whilst the four solid lines represent the measurement results for red, green, blue and grey colours, the dotted line is the sum of the red, green and blue channels. The additivity error for the white colour is 4.60 (ΔE^*_{ab}).

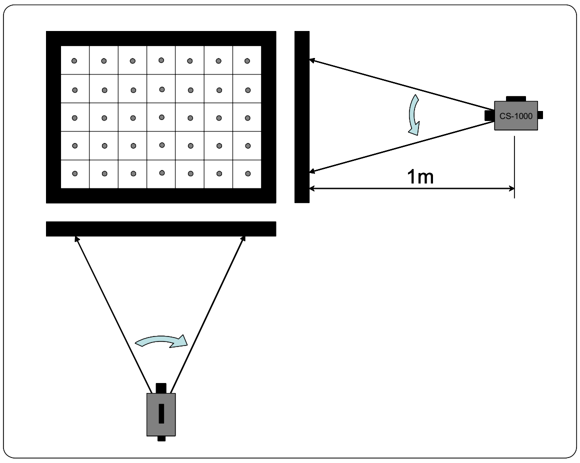


Figure 2. *Setup for spatial uniformity measurement*

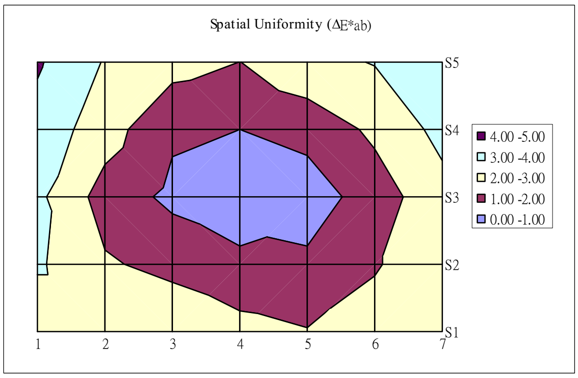


Figure 3. *Spatial uniformity of the EIZO CG220 in terms of* ΔE^*_{ab}

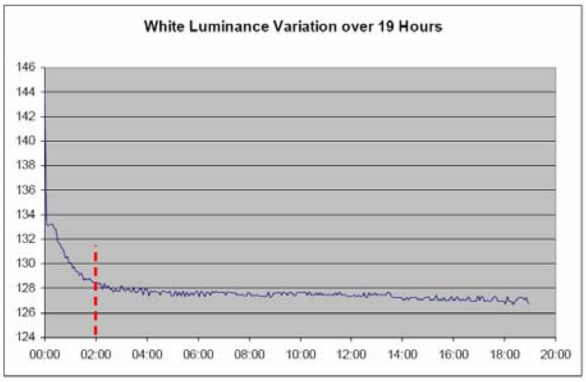


Figure 4. *Temporal stability of the EIZO CG220 display*

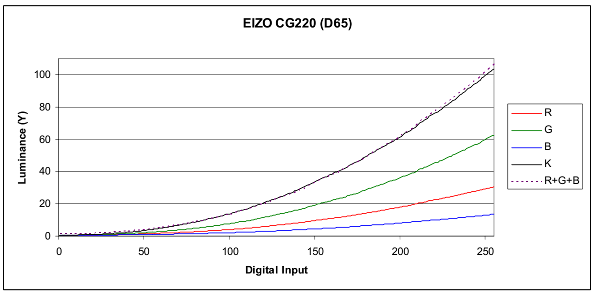


Figure 5. *Tone reproduction curve of the EIZO CG220*

Characterisation Model

The gain-offset-gamma (GOG) model [18] was used to characterise the EIZO CG220 display. Although it is not an accurate model for LCDs due to their failure to fulfil the basic additivity assumption, it nevertheless was a practical way to determine the relationship between input and output signals. In particular for this pilot study, its simple nature provides a good balance between accuracy and measurement time. In order to obtain more accurate results, however, the colour difference results were calculated directly using the measured data.

Experimental Design

The current Mura defect inspection method and criteria defined in the SEMI standard [6] are limited to monochrome backgrounds. In order to understand the influence of Mura on complex-image quality, this research started by investigating the just noticeable difference (JND) values of Mura patterns in different colours having different lightness and chroma.

In this experiment, four opponent colours—red, green, blue and yellow, plus neutral grey—were investigated. The experimental conditions comprise colours varying in two directions (chroma and lightness) at three levels roughly evenly distributed within the gamut volume of the EIZO CG220 display. For neutral colours, only three levels of lightness were used. The aim was to have equal numbers of samples that uniformly span the range of chroma and lightness. Figure 6 shows the background colours in CIELAB a^*b^* and L^*C^* diagrams.

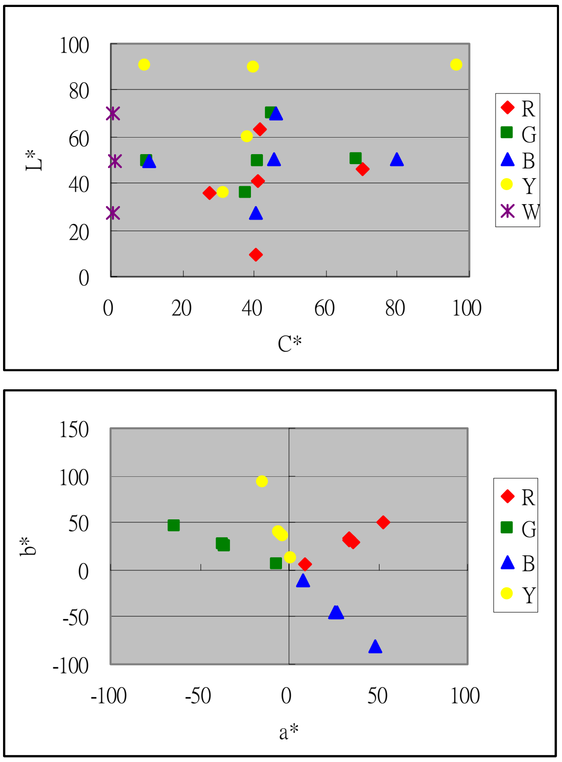


Figure 6. Experimental colours based on the measured data shown in CIELAB colour space. Note that in the L^*-C^* plane, different colours lie at different h_{ab}.

The experiment was conducted in a dark environment to eliminate any influence of ambient light. The luminance of the display's white point was about $100cd/m^2$. Before starting the experiment, observers with normal colour vision were seated around 1m away from the display and were asked to adapt to the dark environment for a few minutes. The task for this experiment was to identify a non-uniform pattern in the centre of the display.

Stimuli

The patterns of the simulated Mura were defined by the two-dimensional Gaussian function defined in Equation (1) [19].

$$Mura(x,y)=L_0*((1+c)*\exp(-(x^2/\sigma^2))*\exp(-(y^2/2\sigma^2))) \qquad (1)$$

where L_0 is the local background luminance, c is the contrast and σ is used as a scaling parameter defining the size of the Mura pattern. A Matlab GUI program was specially designed to generate the desired numbers of Mura patterns at different sizes and rotation angles. In this study, only two different sizes of elliptical Mura patterns were used to simplify the experiment; they were about 1.5°and 4°visual field with their major axes in the vertical direction. By changing the coefficients of Equation (1), it is easy to generate Mura having different sizes and intensities. In brief, the σ value defines the area while L_0 and c together control the intensity of a Mura pattern.

Observers

There were 11 subjects, 9 males and 2 females, with normal vision (the Ishihara test was used), participating in this experiment. None had done visual assessment of Mura defects before. Of them, 4 subjects aged between 20-30; another 4 subjects were between 30-40, and the remaining 3 between 40-50.

Procedure

The experiment was divided into two sessions – ascending and descending. In the ascending session, for each colour the observers were asked to click the "Next" button shown at the bottom of the display to move to the next strongest intensity of the target until they detected it. They then clicked the "Confirm" button.

Upon clicking the "Confirm" button, the system automatically recorded their data and switched to a grey background before proceeding to the next colour under investigation. At this point, the observers would no longer be able to go back to review the previous colour. If they were unsure when they started to detect the Mura pattern, it was possible to use the "Previous" button to move backward to a weaker intensity and identify the intensity level at which they thought they started to detect it. However, moving backward too much is not permitted as this would turn it into the descending part of the experiment.

The next colour would look either similar to, or very different from, the previous one. Therefore, the neutral grey background shown between these two colours provides an opportunity for observers to rest their eyes and reset to their original state. This can eliminate an after-images occurring when suddenly viewing a dramatic change in colour. This adaptation time might vary from person to person and depends on the extent of change between different colours encountered. For example, if the previous colour is grey, the adaptation time could be shorter than a highly chromatic one.

Data Analysis

To analyse the influence of coloured background on the detection of Mura patterns, the assessment results are presented in terms of P0, the percentage of observers detecting a Mura pattern on the LCD, against colour difference (ΔE^*_{ab} or ΔE_{00}). Figure 7 is an ideal example of the procedure for determining a JND value, for which half of the observers see a Mura pattern having colour difference ΔE^*_{ab} and the rest do not. In this procedure, a logistic function having the form of Equation (2) was used to curve-fit the scatter data in order to determine a JND value corresponding to a particular experimental condition. In this equation, parameters u and s determine the inflection point and this logistic distribution function's slope at this point respectively.

$$F(x,u,s) = \frac{1}{1+e^{-(x-u)/s}} \qquad (2)$$

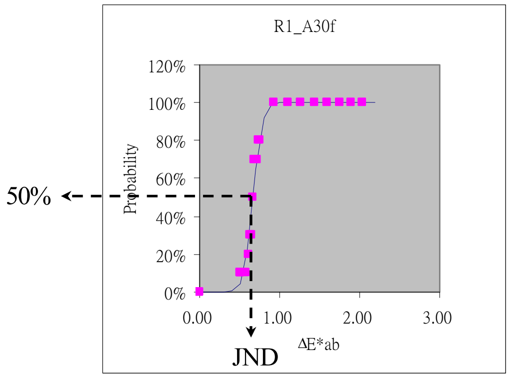


Figure 7. Example of the curve-fitting procedure used to determine the JND value for a particular coloured background

Results

As an important basis for understanding the influence of Mura patterns on complex image quality, the purpose of this study was to investigate how the human visual system's judgment of Mura patterns is affected by different coloured backgrounds. Hence, the experimental design and data analysis were focused on the following aspects:

1. Does the area of Mura affect the trends of results?
2. How does the JND value vary with chroma change?
3. How does the JND value vary with lightness change?
4. How does the JND value vary with different coloured backgrounds?
5. Which factor affects the results the most?

Note that in the following analysis, the notations 'A30' and 'A60' in the figures and tables are used to denote two different sizes of Mura patterns, whilst suffixes '_f' and '_b' represent respectively the ascending and descending parts of the experiments.

The Effect of Mura Size

In Figure 8, the visual assessment results for the large-sized (A60) Mura are plotted against the results for the small-sized (A30) Mura in terms of ΔE^*_{ab} and ΔE_{00}. It can be seen that there were slight deviations for the R5 conditions due to the induction of 50%-cumulative-distribution JND determination procedure. According to this figure, the influence of Mura pattern size was unclear in this experiment. This result, however, is consistent with the findings of previous research [2, 11] when using contrast ratio instead of colour difference as a JND unit. In their research, Mura size was a dominant factor for Mura detection. As a result, this implies that colour difference equations such as CIELAB and CIEDE2000 could take into account the effect of coloured backgrounds on Mura inspection, but they could also underestimate the effect of Mura size. Moreover, this result may also not be applicable to indistinct Mura defects [20] which are large and caused by slight luminance variations in backlighting across the panel. A threshold for the size effect could be further studied in the future.

Since both of the Mura sizes used in this experiment delivered similar results, only the results of large-sized (A60) Mura were used to represent the trends in the following analysis.

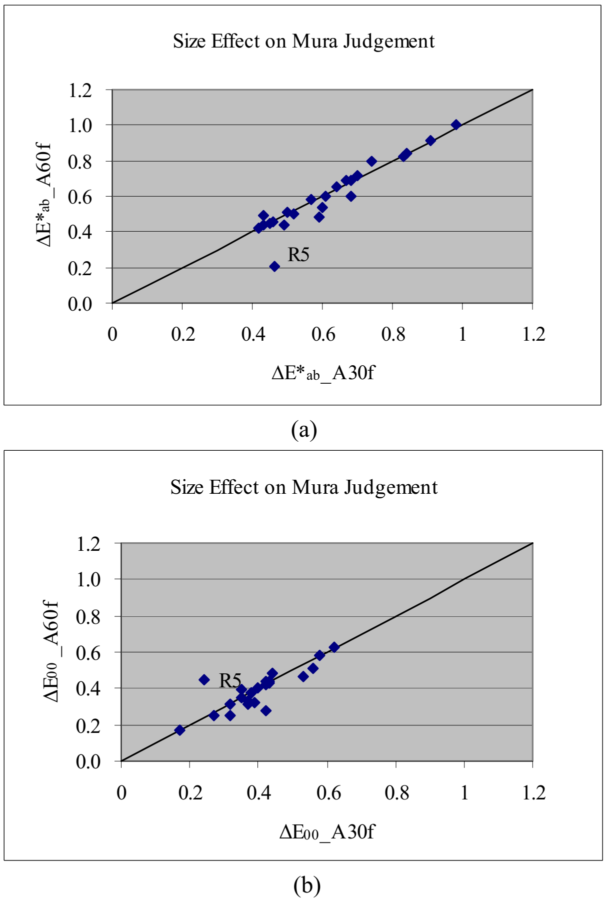


Figure 8. Size effect on Mura detection; results for ascending experiments in terms of (a)ΔE^*_{ab} and (b)ΔE_{00}

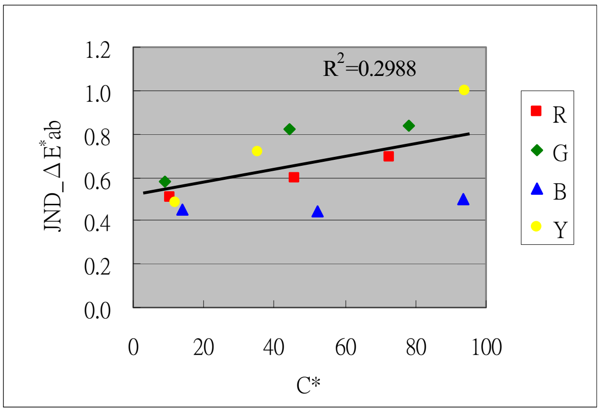
Variation of JND with Chroma

In Figure 9, the JND values of different colours are plotted against chroma. For a specific coloured background, a Mura pattern having a lower JND value has colour differences that are more noticeable.

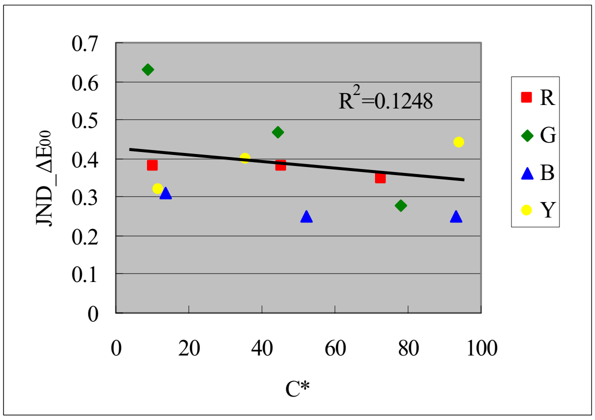
Although the correlation coefficients shown in Figure 8 were not large, the scattering of the JND values seemed to have subtle trends with changes in chroma. For example, when the chroma of the background colours increases, the JND values in terms of ΔE^*_{ab} also increase; when the chroma of the background colours increases, the JND values in terms of ΔE_{00} decrease. Table 2 shows the standard deviations of the JND values obtained from the large-sized (A60) Mura for different chroma. After taking these STD values into consideration however, there is no significant relationship between JND values and chroma. In other words, in this experiment the variation between different data sets is large. For such a condition, the trends produced by the scattered data should be carefully treated. The only certainty is that CIELAB and CIEDE2000 delivered opposite trends in this experiment.

Table 2 Standard deviations of the JND values obtained from the large-sized (A60) Mura for different chroma

C* A60	R	G	B	Y	W
STD_ΔE^*_{ab}	0.24	0.30	0.21	0.36	-
STD_ΔE_{00}	0.17	0.35	0.21	0.16	-



(a)



(b)

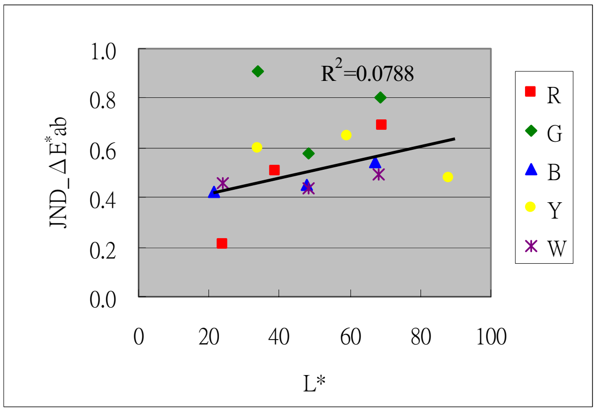
Figure 9. Distributions of JND_A60 values under different C conditions in terms of (a) ΔE^*_{ab} and (b) ΔE_{00}*

Variation of JND with Lightness

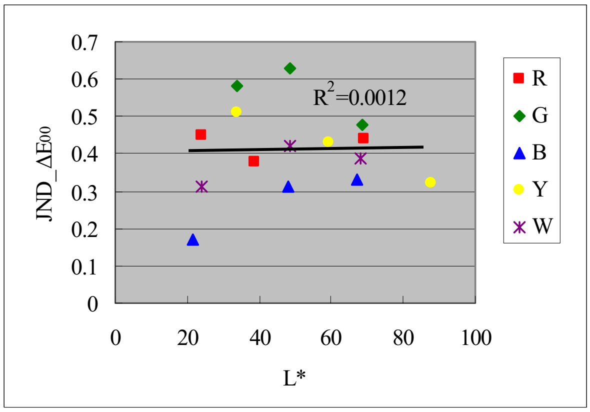
Different experimental conditions induced different JND values. In Figure 10, the JND values (in terms of ΔE^*_{ab} and ΔE_{00}) of large-sized Mura are plotted against lightness. According to the results, the JND values of some colours seem to be influenced greatly as lightness changes, whilst others show only slight variations. However, compared with the correlation coefficients and the STD values (Table 3) of these results, the trends showed insignificant difference to support the idea that different experimental conditions did induce significantly different JND values. That means both formulae showed some variations with lightness; however the results overlapped with each other within one standard deviation unit. On the other hand, to some extent, the results here are similar to that in previous research [12], i.e. JND values did not change significantly with lightness above 10cd/m^2.

Table 3: Standard deviations of the JND values obtained from the large-sized (A60) Mura for different lightness

L* A60	R	G	B	Y	W
STD_ΔE^*_{ab}	0.31	0.37	0.14	0.30	0.22
STD_ΔE_{00}	0.17	0.23	0.11	0.20	0.19



(a)



(b)

Figure 10. Distributions of JND_A60 values under different L conditions in terms of (a) ΔE^*_{ab} and (b) ΔE_{00}*

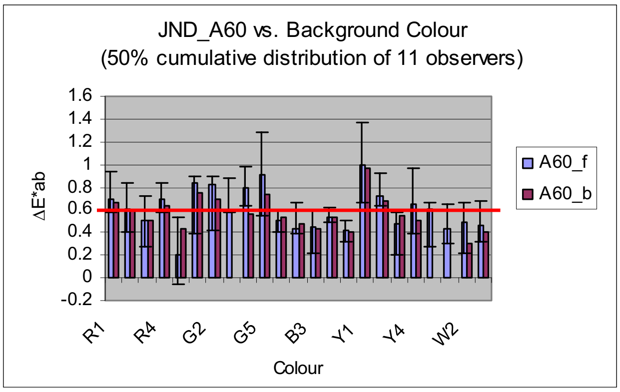
Variation of JND with Coloured Background

In Figure 11, the JND values for all the different colours used in this experiment are shown with error bars of one standard deviation. The red (bold) lines in this figure indicate the mean values of all colours. As can be seen, the JND values range from 0.4 to 1.0 ΔE^*_{ab} units and around 0.2 to 0.6 ΔE_{00} units. This result is similar to the EIZO CG220 LCD's stability (which is 0.23 ΔE^*_{ab} mean with a maximum value of 0.67 ΔE^*_{ab}) after warm-up for two hours, which is relatively insignificant. In spite of the units used for data analysis, they do not show any noticeable difference between colours; however, one thing worth mentioning is that as the CIEDE2000 colour-difference formula is specially designed for small colour-difference calculations, its range is narrower (relative to CIELAB) and leads to a flatter distribution in this column-charts (Figure 11). On the other hand, whilst both CIELAB and CIEDE2000 formulae give similar results for different coloured backgrounds, some colours seem to produce more stable results than other colours.

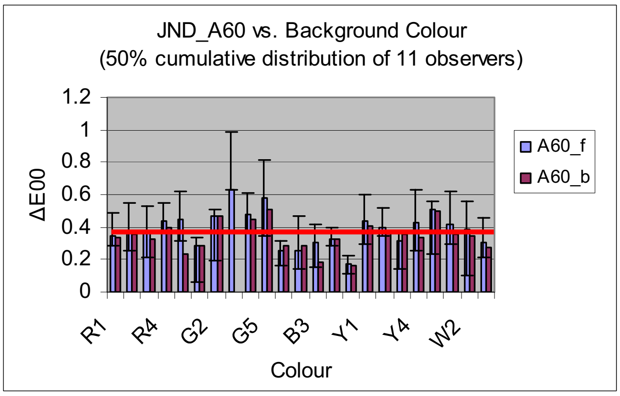
Factors Affecting the Results

It is hard to say which factors influence the results the most. With the use of CIELAB and CIEDE2000 colour-difference formulae, there is no strong statistical evidence that could lead to a clear conclusion about any influence on the trends. That means slight variations in average JND values from all observers were smaller than their standard deviation values. In some ways, this could be good news in that both of these two formulae successfully eliminate the influences of colours and provide an even prediction on thresholds of Mura detection without being disturbed by colour.

Colour and size did cause difficulties to some observers who were unable to maintain consistent thresholds for Mura detection. Although previous analyses indicated that size did not influence the results for specific colour conditions, they did have more consistent results for different sizes and different colour-difference formulae.



(a)



(b)

Figure 11. *JND values varying with background colour in terms of (a)* ΔE^*_{ab} *and (b)* ΔE_{00} *for large-sized (A60) Mura*

Conclusions

The current results showed that both CIELAB and CIEDE2000 colour-difference formulae are suitable for Mura investigation, the somewhat low correlation coefficients imply the models can be further improved. A more sophisticated experimental method and model involving luminance variation profiles could improve the grading results. The experimental technique will also be improved furthering the future study.

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