Necessary colour correction for the implementation of the Cambridge Colour Test on a LCD monitor

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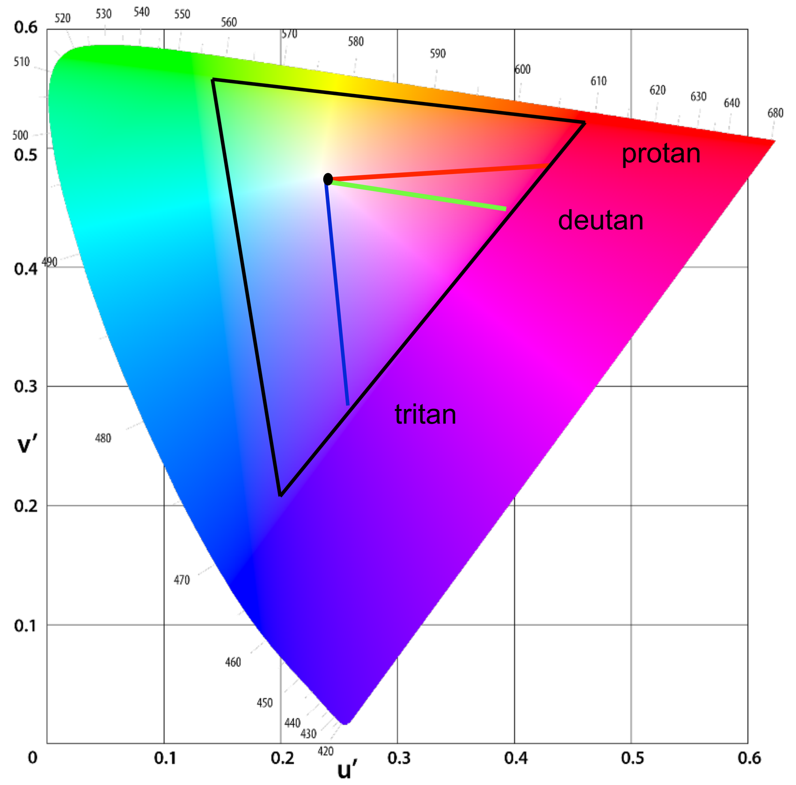
CAMBRIDGE RESEARCH SYSTEMS

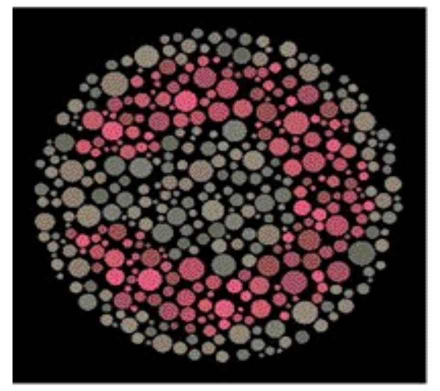
Application background

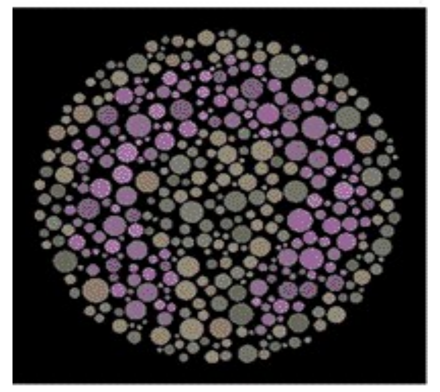
To obtain accurate colour discrimination thresholds, it is crucial that the display device is able to reproduce colour reliably. To achieve this, the original implementation of the CCT used a dedicated Visual Stimulus Generator (VSG)[1] which is capable of generating chromatic stimuli with 14 bit resolution, on a Cathode Ray Tube (CRT) monitor. As CRTs are no longer made, we tested if a calibrated Liquid Crystal Display (LCD) monitor[2] could offer the equivalent performance, and thus be considered as an alternate stimulus display for the CCT.

Cambridge Colour Test (CCT)

The CCT (Regan *et al.* 1994) is a colour discrimination test that measures the minimum amount of saturation required to discriminate a chromatic Landolt C-like ring from its achromatic background.







Colour reproduction

Typically, the colour to be reproduced is specified in some visual units, such as CIE tristimulus values or LMS excitations.

To reproduce those values accurately, we need to:

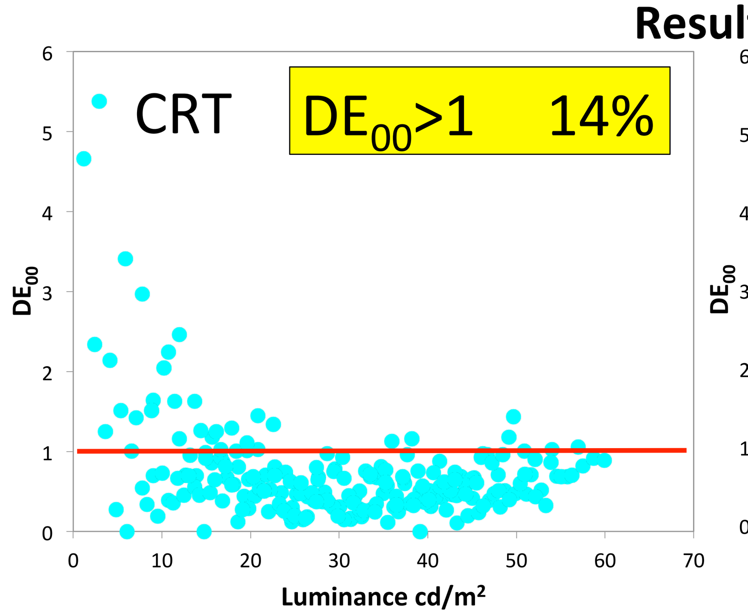
1) find the relationship between the display's digital input values (R, G, B) and their corresponding outputs in visual units (through display characterization and matrix transform **M**).
2) find the inverse relationship between the visual units and the digital values (by using the inverse matrix transform **M**[-1]).

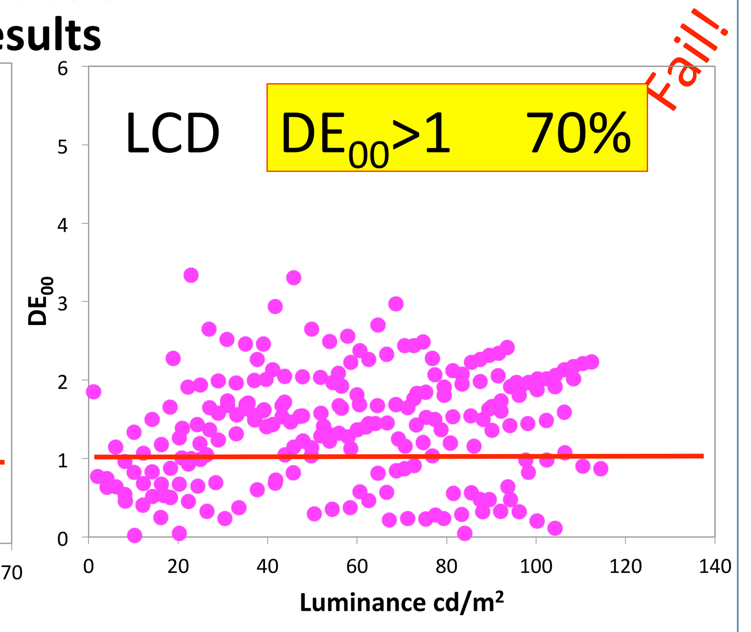
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \underbrace{\begin{pmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{pmatrix}}_{\mathbf{M}} \times \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad \begin{pmatrix} R \\ G \\ B \end{pmatrix} = \mathbf{M}^{-1} \times \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

Native colour reproduction

We characterised[3] the performance of two display types, a 22" Mitsubishi CRT and a 32" Display++ LCD, to reproduce a set of chromatic stimuli, and calculated the just noticeable difference between the measured and the requested colour using the delta E (DE_{00}). A value of $DE_{00}>1$ represents a visible difference between the requested and the measured colour.

Results



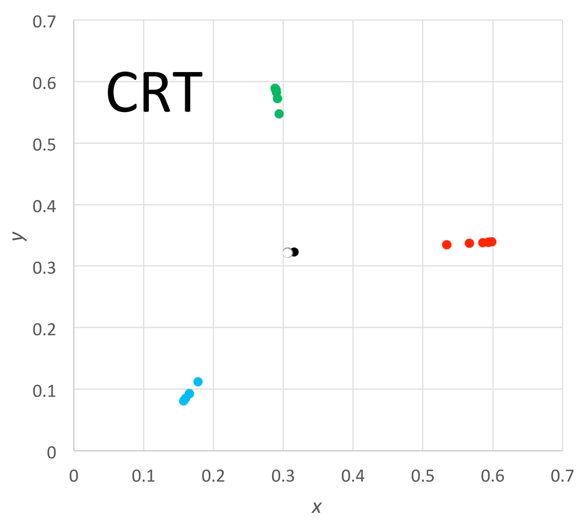


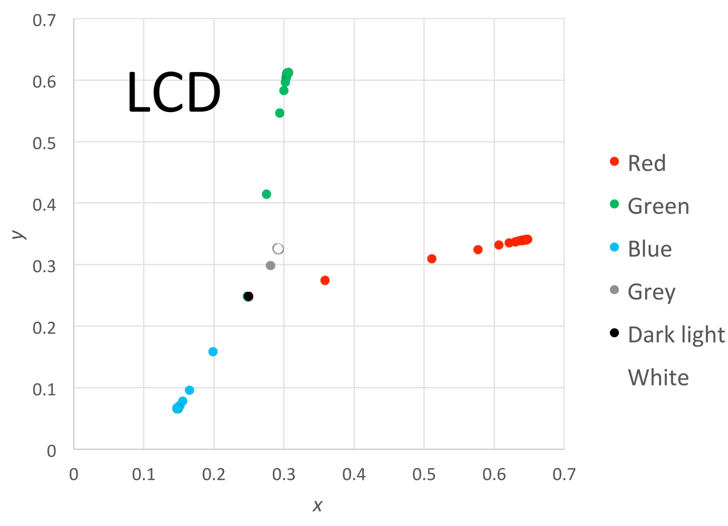
Why is colour reproduction poor?

The 3x3 matrix transform provides accurate colour reproduction as long as the primaries are independent and additive, and their chromaticities are constant across light levels.

Both CRTs and LCDs can show a failure of the above assumptions. CRTs often show cross-talk of the primaries due to inaccuracies of the electron beams in hitting the phosphors. LCDs suffer from interference between the charges stored on neighboring subpixels (see also note 1).

Chromaticity shift





Additional factors

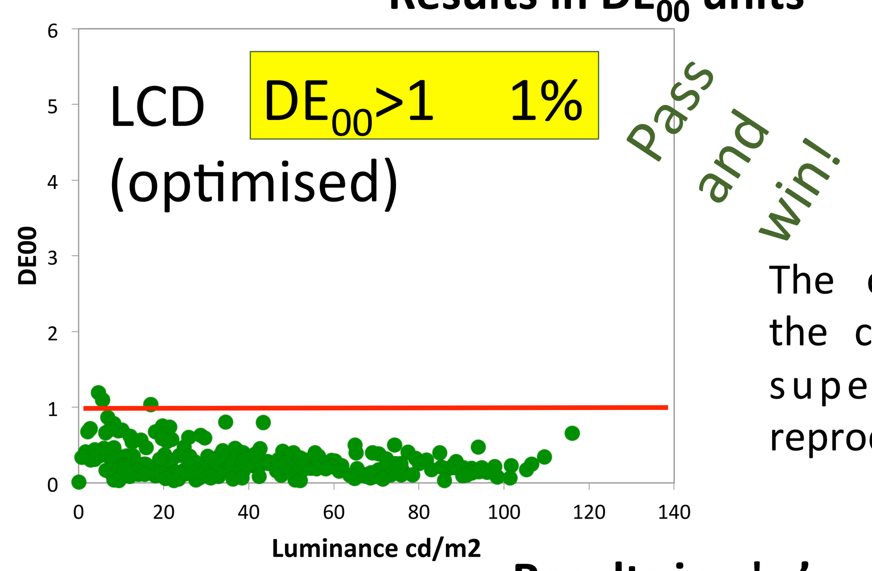
There appear to be additional factors that can contribute to this inaccuracy, including:

(i) variations in the LC transmittance properties due to changes in temperature[2];
(ii) goodness of the opto-electronic transfer function characterisation and its linearisation;
(iii) contribution of the dark light;
(iv) colour resolution of the LCD.

Optimised colour reproduction

We have developed a novel optimized colour correction (Ripamonti *et al.* 2015) based on a high (16-bit) colour resolution LCD system[2] and a large set of XYZ input measurements (13x13x13). The correction takes into account: (a) the interdependence of the primaries; (b) the chromaticity shift; and (c) an optimal linearization process.

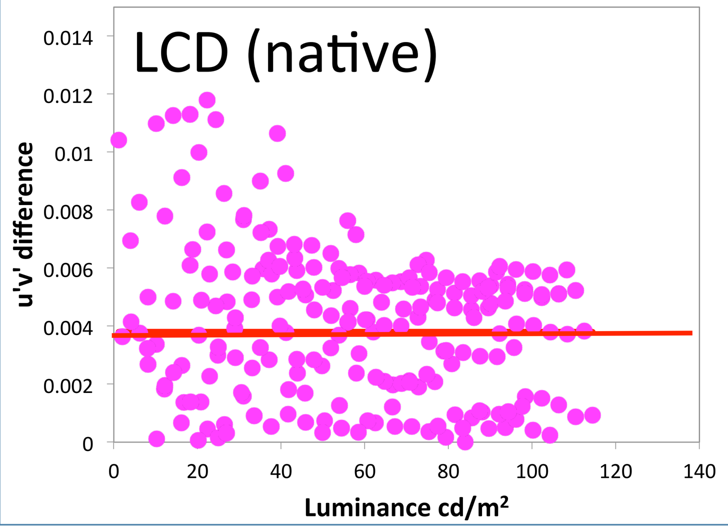
Results in DE_{00} units

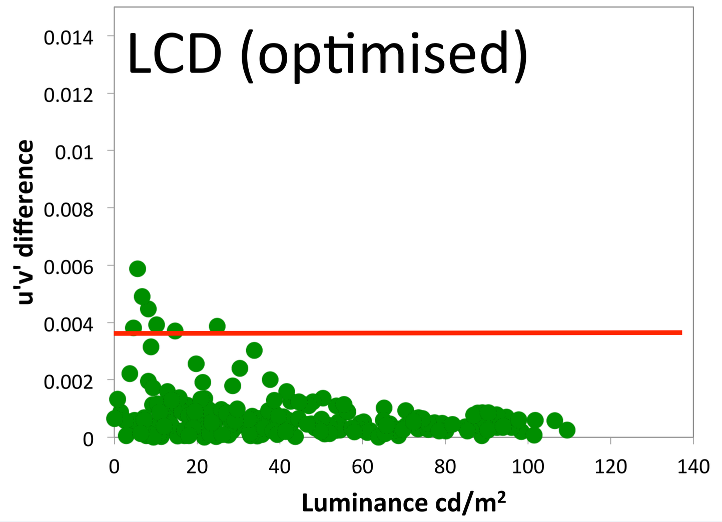


The colour reproduction of the colour corrected LCD is superior to the colour reproduction of the CRT.

Results in u' v'

To calculated the difference between the measured and the requested colour only in terms of colour shift, we considered a second index which is based only on the difference between the u'v' chromaticity coordinates. The JND corresponds to the mean thresholds measured in the CCT experiment.





Notes

[1] The native resolution of the VSG (Cambridge research Systems, Ltd) analogue video output is 14-bits.

[2] The Display++ LCD (CRS, Ltd) was connected to an Apple iMac with Intel Iris Pro graphics. The CCT was re-implemented using the Psykinematix Sharp Edition software running on OSX. The native resolution of this system is 10-bits which has been extended to a maximum of 16-bits using a proprietary temporal dithering mode.

[3] Measurements were taken using SpectroCAL MKII spectroradiometer (CRS Ltd).

3. The chromaticity shift can occur because the LC polarization is not precisely the same for all wavelengths and also as a result of spectral variations in polarizer extinction (Wandell and Silverstein, 2003).

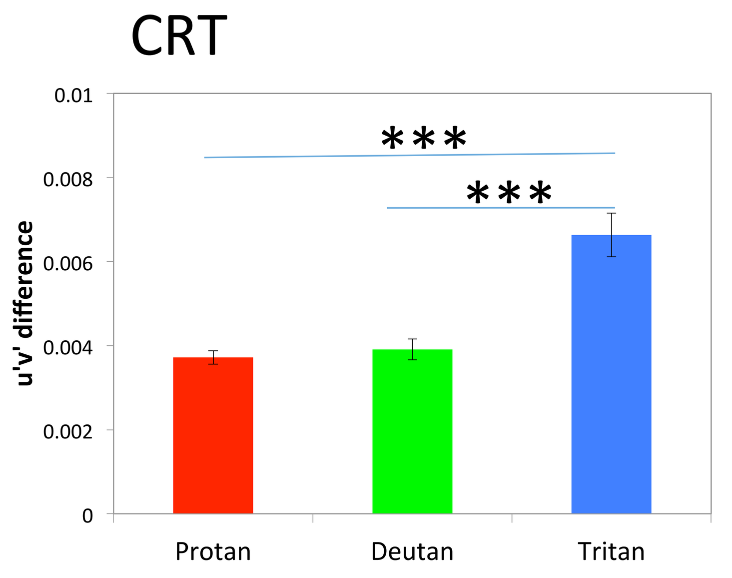
4. Display++ has a luminance-control-loop built in that corrects for any drift in the light output over time.

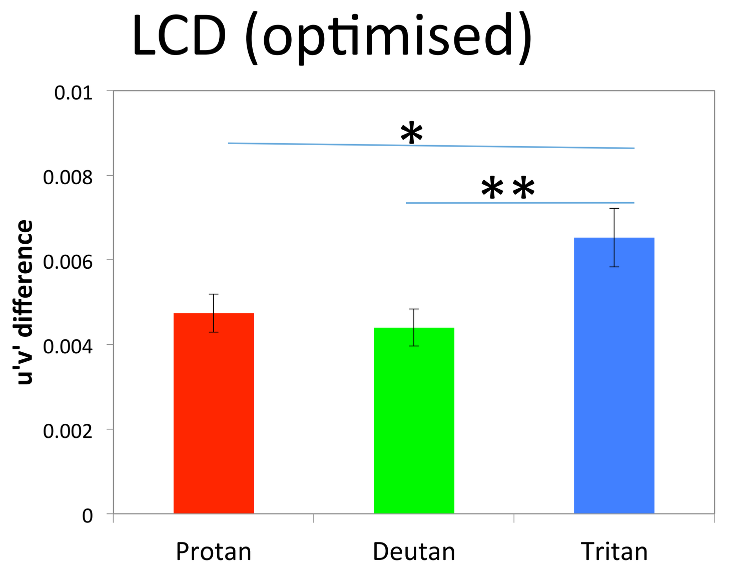
CCT Experiment

We ran the CCT on a group of 7 naïve observers (37-49 years, median 45 years) to test whether the colour discrimination thresholds collected with the CRT system[1] were different from the thresholds collected with the LCD system[2] with an optimised colour reproduction.

Results

We found that the thresholds measured with the LCD were not statistically different from the CRT thresholds [Protan: t(20)=-2.5, p=.02; Deutan: t(20)=-1.13, p=.268; Tritan: t(20)=.141, p=.889].





Furthermore, we found that both tests consistently revealed that the Tritan thresholds were significantly higher than the Protan [CRT: t(20)=-5.8, p=.000; LCD: t(20)=2.4, p=.02)] and Deutan [CRT: t(20)=-5.6, p=.000; LCD: t(20)=3.8, p=.001] thresholds.

Conclusions

Our aim is to achieve accurate colour reproduction for stimuli used in colour vision experiments.

To do so, we have developed an optimised colorimetric correction which takes into account critical factors that affect colour reproduction. We show that our numerical optimisation can significantly improve the colour reproduction of a calibrated LCD. Using our optimised colour correction algorithm, less than 1% of the colours reproduced by the LCD had a DE>1. This demonstrates that our calibrated LCD has superior colour reproduction compared to the native performance of a CRT display, and provides the confidence that we can re-implement the CCT on this system.

References

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Ripamonti, Hodgetts, and Thomassen (2015). A comparison of display technologies for accurate reproduction of colour stimuli. J Vis., 15(12):1319.

Day, Taplin, and Berns (2004). Colorimetric characterization of a computer-controlled liquid crystal display. CR&A, 29(5), pp. 365–373.

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