The CIE94 colour difference formula for describing visual detection thresholds in static noise

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Abstract

The parametric factors k_L, k_C and k_H that scale the CIELAB components ΔL^*, ΔC^* and ΔH^* in the CIE94 colour difference formula are unity under reference conditions. When the conditions are changed, the scaling factors may be adapted to account for the influence of specific experimental conditions on perceived colour differences. We determined thresholds for the visibility of static background noise and for the visibility of a test symbol. The noise was present in only one of the L^*, C^* or H^* dimensions, and the test symbol was an increment to the background, also in one of the dimensions L^*, C^* or H^*. In order to maintain a perceptual uniform difference metric between test symbol and noisy background we arrived at $k_L = 0.15$, $k_C = 0.52$, and $k_H = 2.21$, such that a just noticeable difference corresponds to $\Delta E^*_{94}=1$. When the dimension (L^*, C^* or h^*) of the incremental test symbol is the same as that of the noise in the background, the threshold for the test symbol increases linearly with the noise. When the dimensions are different, the thresholds for the test symbol remain constant (background noise in L^*) or slowly increase (background noise in C^* or h^*).

Introduction

The CIE94 colour difference is defined as

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*}{k_H S_H}\right)^2} \qquad (1)$$

in which the CIELAB components ΔL^*, ΔC^* and ΔH^* represent differences in lightness, chroma and hue, respectively (CIE, 1995). These three components are scaled by individual factors *S* and *k*. The *S*-factors are intended to improve the perceptual uniformity of CIELAB colour space, having values of S_L=1, S_C=1+0.045 C^* and S_H=1+0.015 C^*. Under reference conditions (ref CIE 116) the *k*-factors (known as parametric factors) are set to $k_L = k_C = k_H = 1$. When deviating from the reference conditions these *k*-factors may be adapted to account for the influence of specific experimental conditions on perceived colour differences. We are interested in finding out how the scaling should be done in order to accommodate the results of visual detection experiments with stimuli as shown in Fig. 1.

Methods

Stimuli

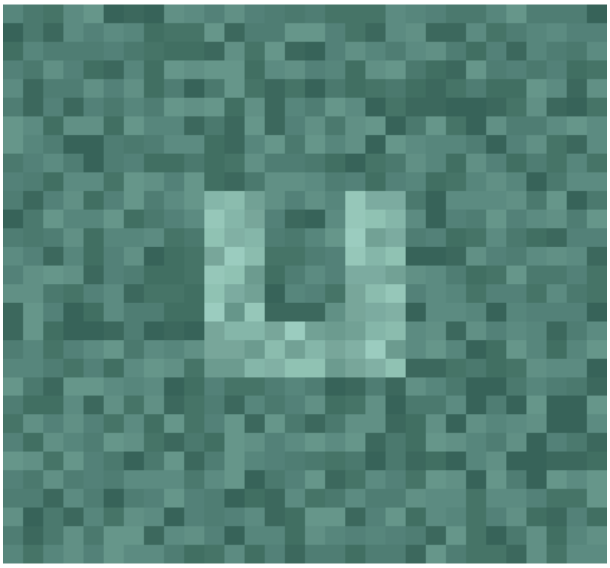

Figure 1: Stimulus example for L=50, C*=20, h*=180. Both the background noise and the test symbol can be specifically adjusted in L*, C* or h* (9 combinations possible). Shown here is a combination of background noise in L* and incremental test symbol in L*.*

Our stimuli were built up as an array of 30x30 squares, each square subtending a visual angle of 0.58° at our standard viewing distance of 0.5 m. Each square could be addressed with an individual colour specification. On an average background colour, "noise" could be added in one of the three dimensions L^*, C^* or H^* (but not simultaneously in two or three). In order to stay within the colour gamut of the display as much as possible, we selected a working point at L^*=50, C^*=20 and used six values of the hue angle (h^*=0, 60, 120, 180, 240, 300). The strength of the background noise was controlled by the value of ΔE^*_{94}. For example, when ΔE^*_{94} was set to a value of 2 in the L^*-dimension, this meant that each square was randomly assigned an L^*-value in between 50-2=48 and 50+2=52, maintaining an average of

L^*=50. We restricted the noise to 11 discrete levels (5 below the average, 5 above the average, and the average) uniformly distributed over the range [average - ΔE^*_{94}, average + ΔE^*_{94}]. In the center of the stimulus we could also produce a U-shaped test symbol as an increment to the background. This test symbol was three squares thick and 10x10 squares large, with an opening on one of the four sides. The increment was defined as an increment in one of the L^*, C^* or H^* dimension (but not simultaneously in two or three), so that nine combinations of background noise and incremental test symbol could be studied.

Display calibration

Our stimuli were generated on a calibrated CRT and LCD-display. Using a Photo Research PR650 spectroradiometer we measured the CIE 1931 X,Y,Z tristimulus values of our monitor, at 18 points along each of the separately driven R, G and B primary channels, and at R=G=B. We apply the usual transformation matrix between target X,Y,Z and primary luminances Y_{red}, Y_{green}, Y_{blue} (e.g. Berns, 1996), and interpolation along the primary tone characteristics in order to get the R, G, B drive values (0-255) required for generating specified colours on the CRT. For the LCD we do the same, however the measurement data are first modified to account for the inter channel dependency and black level problems typically associated with LCD displays (Cazes *et al*., 1999).

Procedure

Three subjects participated in the experiment, the two authors and one naive as to the purpose of the experiments. All had normal or corrected to normal visual acuity and normal colour vision. The subjects saw the stimulus displays from a viewing distance of 0.5 m in an otherwise darkened room. By adjusting the value of ΔE^*_{94} on the graphical user interface of our software that generated the stimuli (method of adjustment), the subjects determined the threshold value of ΔE^*_{94} at which they could just perceive the background having noise (Experiment 1, in absence of the test symbol) or the correct orientation of our test symbol (Experiment 2) at given background noise.

Results

Experiment 1: thresholds for background noise

In the first experiment the subjects determined thresholds for the visibility of "noise" in the background colour. The noise was applied in L^*, C^* or H^* at L^*=50, C^*=20 and for six values of the hue angle (h^*=0, 60, 120, 180, 240, 300). There was no test symbol. The amount of background noise was set by the value of ΔE^*_{94}, while the parametric factors remained at values $k_L = k_C = k_H$ = 1. In Fig. 2 the results are shown, both for the LCD-display (Fig. 2a) and the CRT-display (Fig. 2b).

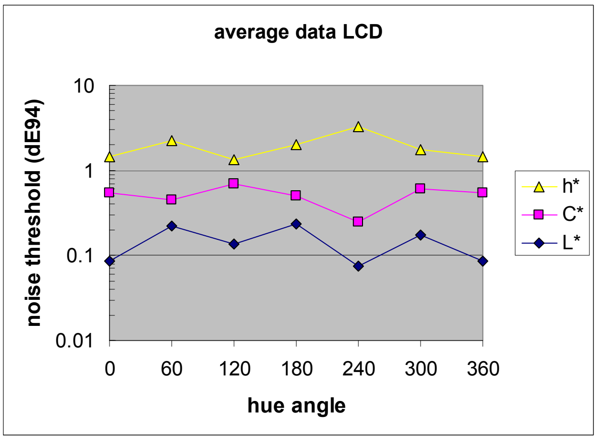

Figure 2a. Average data of subjects PB and ML, obtained on LCD-display. A value of 1 on the vertical axis corresponds to ΔE^*_{94}=1. The data for h=360 is copied from h*=0.*

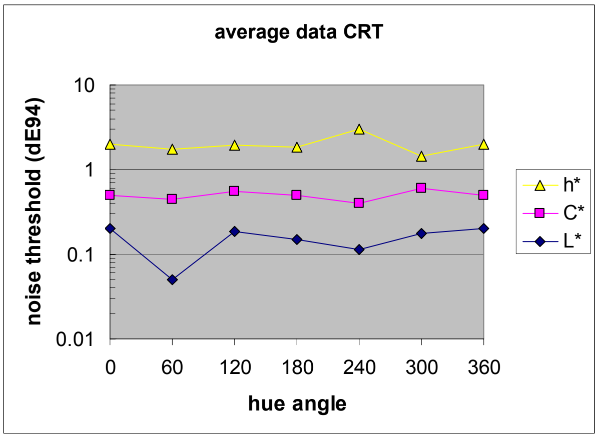

Figure 2b. Average data of subjects ML and EK, obtained on CRT-display.

When comparing the average data for the two types of display, the most striking difference is for the L^*-data at h^*=60. Most interesting, however, is the fact that the thresholds for the visibility of noise in L^*, C^* and h^* levels are well separated. Apparently, for our experimental conditions the noise in L^* is detected about 3 times better than noise in C^* and about 20 times better than noise in h^*. This is the more or less expected result considering the difference in spatial contrast sensitivity functions for luminance and chromatic mechanisms (e.g. Fairchild, 1998).

Experiment 2: thresholds for test symbol identification

In the second experiment we set the parametric factors to the values of k_L = 0.15, k_C = 0.52 and k_H = 2.21. These are the values obtained when averaging the threshold data in Fig. 2 over the six hue angles (for this moment we ignore potential interesting deviations from the averaged threshold values). As a result, a value of ΔE^*_{94}=1 in eq. (1) for the background noise corresponds to 1 JND (just noticeable difference) in L^*, C^* and H^*.

For five values of the background noise, ΔE^*_{94}= 0, 5, 10, 15 and 20, the subjects determined the threshold value of ΔE^*_{94} that specified the difference between the background and the test symbol. The subjects had to indicate the orientation of the opening in the test symbol (left, up, right or down), which was randomly selected by our computer program each time the value of ΔE^*_{94} was changed. The threshold was found by first decreasing the value of ΔE^*_{94} until errors were made in the reported orientation of the test symbol, after which the value of ΔE^*_{94} was increased again to verify the level at which no errors were made. Figures 3a, 3b and 3c shows the average data for subjects EK and ML, obtained on CRT-display. Each data point represents 12 threshold measurements (2 subjects, 6 hue angles).

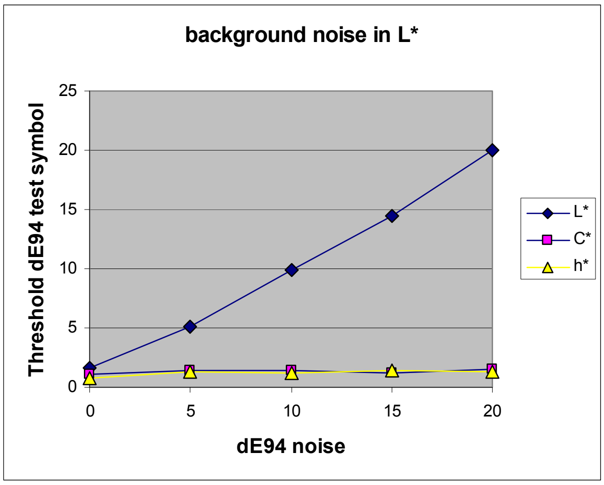

Figure 3a. Threshold ΔE^*_{94} required for visibility of the test symbol on different background noise levels in dimension L^*. The values along the axes represent the number of JND's.

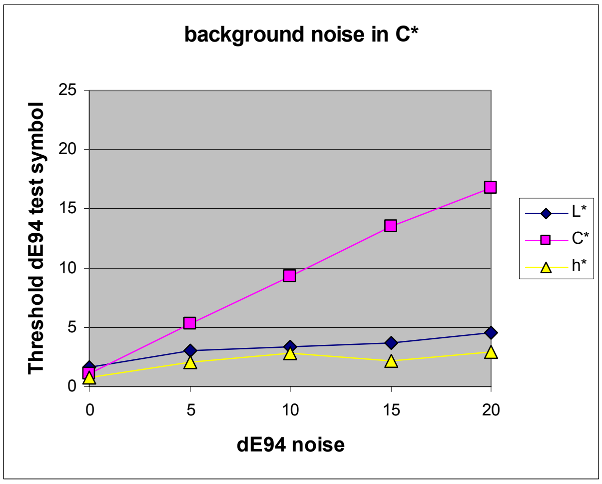

Figure 3b. Threshold ΔE^*_{94} required for visibility of the test symbol on different background noise levels in dimension C^*.

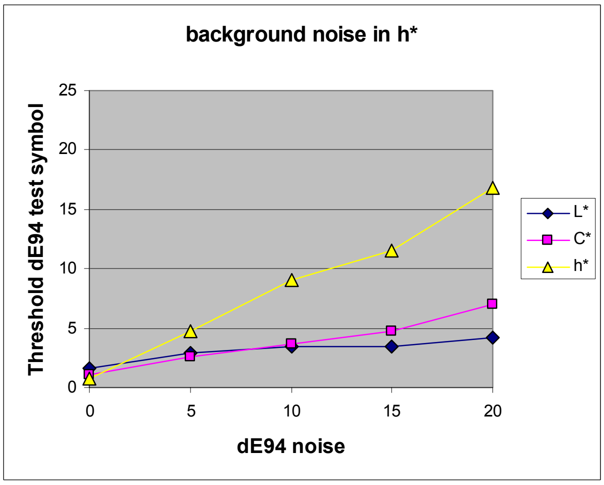

Figure 3c. Threshold ΔE^*_{94} required for visibility of the test symbol on different background noise levels in dimension H^*.

Figures 3a-c show that when the dimension (L^*, C^* or h^*) of the incremental test symbol is the same as that of the noise in the background, the threshold value of ΔE^*_{94} for the test symbol increases linearly with the ΔE^*_{94} of the noise. When the dimensions are different, the thresholds remain constant (noise in L^*) or slowly increase (noise in C^* or h^*) with the level of the background noise.

Discussion

We have shown how to set the scale factors k_L, k_C and k_H in the CIE94 colour difference formula to account for our particular experimental conditions, thereby maintaining an approximate perceptually uniform difference metric between test symbol and noisy background. Of particular interest for applications such as multi-band false-colour imaging and the design of vision tests is that chromatic signals (in C^* or h^*) remain best visible against static noise in L^*. In the temporal domain Chaparro *et al.* (1993) have shown that flashes in the chromatic domain are better detected than in the luminance domain. We intend to further investigate the dependence of the scale factors on viewing distance and resolution of the stimulus array, and with test symbols and background noise that vary in more than just one of the L^*, C^*, h^* dimensions.

References

1. Berns, R.S. Methods for characterizing CRT displays. Displays, 16, 173-182 (1996).
2. Cazes, A., Braudaway, G., Christensen, J. Cordes, M., DeCain, D., Lien, A., Mintzer, F. Wright, S.L. On the color calibration of liquid crystal displays, Proc. IS&T/SPIE Conference on Display Metrology San Jose, 154-161 (1999).

3. Chaparro, A., Stromeyer, C.F. III, Huang, E.P., Kronauer, R.E. & Eskew, R.T. Colour is what the eye sees best. Nature, 361, 348-350 (1993).
4. CIE Pub. 116-1995, Industrial colour-difference evaluation. Vienna: CIE Central Bureau; 1995.
5. Fairchild, M.D. Colour appearance models. Addison-Wesley, Reading, MA, 1998.

Biography

Marcel Lucassen received his M.S. degree in Technical Physics from the Twente University at Enschede (The Netherlands) in 1988 and a Ph.D. in Biophysics from Utrecht University in 1993. From 1993-1999 he worked at the Colorimetry department of Akzo Nobel Coatings on topics related to automated colour matching of car refinishing coatings. Since 1999 he has worked at TNO Human Factors and is currently heading the Vision and Imaging Group. His interests lie in both fundamental and applied colour vision research. He is an IS&T-member and associate editor for Color Research and Application.