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# A Study of Spatial Chromatic Contrast Sensitivity Based on Different Colour Background

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## Abstract

*The goals of this work are to accumulate the experimental data on contrast sensitivity functions and to establish a visual model that incorporates spatial frequency dependence. In addition, the experimental results from fixed-size and fixed-cycles stimuli and from different luminance levels were compared. Such a model is highly desired for applications that rely on image quality and to serve the lighting and imaging industries. The detection thresholds have been measured for chromatic contrast patterns at different spatial frequencies. The experimental parameters included: (1) four colour centres (white, green, yellow and red), which were recommended by the International Commission on Illumination (CIE), at two different luminance levels for each colour centre; (2) three colour directions for each colour centre, namely luminance, red-green and yellow-blue; (3) five spatial frequencies, 0.06, 0.24, 0.96, 3.84 and 6.00 cycles per degree (cpd) for fixed-cycles stimulation, in which two spatial frequencies, 0.24 and 6.00 cpd, were also chosen for fixed-size stimuli. In this experiment, a 10-bit display characterized by GOG model was used to obtain contrast thresholds of different colour centres by 2-alternative forced choice method and stair-case method. The experimental results revealed different parameter effects (colour centres, luminance, colour direction, fixed cycle/size), and also supported McCann's conclusion that the number of cycles affects the comparative sensitivity. Most importantly, a cone contrast model was successfully developed by fitting the visual test data (fixed number of cycles). The model could accurately predict the contrast sensitivity of different color centers, spatial frequencies and stimulus.*

## Introduction

The human visual system is known to have different sensitivities for contrast patterns at different spatial frequencies. The function to describe this dependence for simple sinusoidal patterns is called the contrast sensitivity function (CSF) where sensitivity is defined as the inverse of the contrast at threshold. Equation (1) gives the contrast sensitivity:

$$S = \left(\frac{1}{\sqrt{3}}\sqrt{\left(\frac{\Delta L}{L_0}\right)^2 + \left(\frac{\Delta M}{M_0}\right)^2 + \left(\frac{\Delta S}{S_0}\right)^2}\right)^{-1}. \quad (1)$$

The CSF for luminance patterns has been studied extensively, leading to the establishment of robust models such as that of Barten [1]. Barten developed two models: one that is a physiologically inspired complex model and the other that is relatively simple and empirically fitted to psychophysical data.

Unlike the luminance CSF, the chromatic CSF (CCSF) depends on the direction of the colour modulation, typically involving modulations in red-green and yellow-blue directions with luminance being held constant.

Since the 1950s, many visual psychophysical experiments have been carried out to investigate chromatic contrast sensitivity, usually using sine-wave patterns modulated in different colour directions [2-13].

Zhang and Wandell [14] proposed S-CIELAB metric, which calculates spatial colour difference between images in the colour opponent space. Each colour channel is filtered by a contrast sensitivity function.

Mantiuk et al. [15] developed a cone contrast model to predict contrast sensitivity for luminance levels up to 10,000 *cd/m*$^2$. In the cone contrast model, the cone contrast was combined to form opponent mechanism responses (achromatic, R-G and Y-B) using equation (2):

$$\begin{bmatrix}\Delta C_A\\ \Delta C_R\\ \Delta C_B\end{bmatrix} = \begin{bmatrix}1 & m_{1,2} & m_{1,3}\\ 1 & -m_{2,2} & m_{2,3}\\ -m_{3,1} & -m_{3,2} & 1\end{bmatrix}\cdot\begin{bmatrix}\Delta L/L_0\\ \Delta M/M_0\\ \Delta S/S_0\end{bmatrix}, \quad (2)$$

where $L_0$, $M_0$ and $S_0$ are the coordinates of the colour centre (background colour). The $m_{i,j}$ are the parameters of the transformation matrix.

The responeses of the three postreceptoral mechanisms are weighted by the contrast sensitivity functions and calculated as Minkowski distance with exponent $p$ (equation (3)):

$$E = \left(\sum_{c\in\{A,R,B\}}(S_C(sf,Y,a)\Delta C_C)^p\right)^{1/p}, \quad (3)$$

where $S_A$, $S_R$ and $S_B$ are the sensitivity functions of spatial frequency $sf$ (*cpd*), stimulus size $a$ (*deg*$^2$) and the background luminance $Y$ (*cd/m*$^2$).

The cone contrast model can be used to calculate the response (equation (4)), which is linearly related to the cone increments $\Delta L$, $\Delta M$ and $\Delta S$. A scaling factor was introduced and the new cone increments are given in equation (4):

$$\Delta L' = t\Delta L,\ \Delta M' = t\Delta M,\ \Delta S' = t\Delta S. \quad (4)$$

And the new response is given in equation (5):

$$E' = t\left(\sum_{c\in\{A,R,B\}}(S_C(sf,Y,a)\Delta C_C)^p\right)^{1/p} = tE. \quad (5)$$

The new response $E'$ is 1 for the detection threshold, therefore $t = 1/E$, where $E$ is the original response. Then, the predicted sensitivity is given in equation (6):

$$\tilde{S} = \left( \frac{1}{\sqrt{3}} \sqrt{ \left(\frac{t\Delta L}{L_0}\right)^2 + \left(\frac{t\Delta M}{M_0}\right)^2 + \left(\frac{t\Delta S}{S_0}\right)^2 } \right)^{-1} )^{-1}. \quad (6)$$

Mantiuk et al. model sensitivity function as a product of inverse log-parabola and a modified stimulus size term. The sensitivity function is given in equation (7):

$$S_C(sf, Y, a) = \frac{\hat{S}_C(Y)}{p_C(sf)} \sqrt{\frac{a^{\gamma_C} \cdot sf^2}{k_C(a) + a^{\gamma_C} \cdot sf^2}}, \quad (7)$$

where $C$ represents the mechanism $(A, R, B)$. The function is given in equation (8):

$$k_C(a) = \hat{a}_C + a\hat{f}_C. \quad (8)$$

The log parabola function is given in equation (9):

$$p_C(sf) = \begin{cases} 1 & c \in \{R, B\} \; and \; sf < \widehat{sf}_C \\ 10^{\frac{(log_{10}(sf) - log_{10}(\widehat{sf}_C(Y)))^2}{2^{b_C - 1}}} & otherwise \end{cases}. \quad (9)$$

The peak-frequency is given in equation (10):

$$\widehat{sf}_C(Y) = \begin{cases} \rho_{A1}^{\left(\frac{1+\rho_{A2}}{Y}\right)^{\rho_{A3}}} & c = A \\ \rho_C & c \in \{R, B\} \end{cases}. \quad (10)$$

The base-sensitivity is given in equation (11):

$$\hat{S}_C(Y) = \begin{cases} s_{A1} (\frac{1+s_{A2}}{Y})^{s_{A3}} (1 - \frac{1+s_{A4}}{Y})^{s_{A5}} & c = A \\ s_{C1} (\frac{1+s_{C2}}{Y})^{s_{C3}} & c \in \{R, B\} \end{cases}. \quad (11)$$

The goal of the present research is to accumulate reliable experimental data and to develop robust CSFs. A threshold method based on forced-choice stair-case was adopted to assess just noticeable or threshold colour difference of fixed-cycles and fixed-size stimuli in 3 colour changing directions at 5 spatial frequencies. A cone contrast model was developed by fitting the data.

## Experiment

### *Stimulus*

The experiment was conducted in a dark room. Spatial chromatic patterns were presented on a 10-bit 'NEC PA311D' LCD display with 2560 × 1440 pixels, which was set at a constant peak luminance of either 300 or 100 *cd/m²* and calibrated using a Gain-Offset-Gamma (GOG) [16] model. All the measurements were conducted using a Konica Minolta CS2000A tele-spectroradiometer. All results were reported for the CIE 1964 standard colorimetric observer. The display had a mean prediction accuracy of 0.65 $\Delta E^*_{ab}$ (0.47 $\Delta E_{00}$) and 0.66 $\Delta E^*_{ab}$ (0.51 $\Delta E_{00}$) from the colour patches of 24 colours on an X-Rite Macbeth ColorChecker chart (MCCC) for 300 and 100 *cd/m²*, respectively. The relatively small colour differences reported for each parameter measured suggest that the display provides high quality, repeatable images and was suitable for the visual experiments.

The uniformity property was tested by measuring 9 equal portions (3 by 3) of the screen. Four colours were measured, i.e., white, red, green and blue. The mean colour difference was 0.61 $\Delta E_{00}$, which is relatively small.

The colour backgrounds (colur centres) were selected close to the 4 CIE centres recommended to study colour difference [17], i.e., white (W), red (R), yellow (Y) and green (G), at two different luminance levels, high (H) and low (L) levels, for each colour centre. The colour centres were represented as WH, WL, RH, RL, YH, YL, GH and GL respectively. Table 1 lists the chromaticity of the colour centres. The display peak white was set at either 300 or 100 *cd/m²* for the colour centres brighter or darker than 50 *cd/m²*, respectively. The colour stimulus was modulated along three colour directions for each colour centre, i.e., luminance (achromatic), red-green (R-G) and yellow-blue (Y-B). Five spatial frequencies, 0.06, 0.24, 0.96, 3.84 and 6.00 cycles per degree (cpd) were selected for fixed-cycles stimulation, in which two spatial frequencies, 0.24 and 6.00 cpd, were also chosen for fixed-size stimuli. Totally 7 spatial frequencies were investigated.

**Table 1: Chromaticity of the colour centres**

| | x | y | L (cd/m²) |
|---|---|---|---|
| WH | 0.314 | 0.331 | 216 |
| WL | 0.314 | 0.331 | 36 |
| RH | 0.484 | 0.342 | 14.1 |
| RL | 0.484 | 0.342 | 7.1 |
| YH | 0.388 | 0.428 | 150 |
| YL | 0.388 | 0.428 | 50 |
| GH | 0.248 | 0.362 | 72 |
| GL | 0.248 | 0.362 | 24 |

Each observer viewed the screen from a distance of 60 centimeters and the total field of view (FoV) was 60° × 34°. Figure 1 shows an example of the chromatic patterns. The chromaticity difference was multiplied with a Gaussian-shaped function (σ of 0.5/sf for fixed cycles, and 34°/4=8.5° for fixed-size) to eliminate the effect of the edges. The background chromaticity of the screen was the same as the colour centre of the sinusoidal pattern. The patterns were oriented either horizontally or vertically. It is assumed that both patterns would give the same threshold [10, 13].

***Figure 1.*** *Chromatic patterns for fixed-cycles stimuli.*

### *Observers*

In total, 40 observers took part in the experiment (26 male and 14 female), varying in age from 20 to 28 years, with a mean age of 23 (standard deviation is 1.9). Each carried out the experiment for 2 out of 8 colour centres. For each colour centre, 10 observers took part. All observers had normal visual acuity of 1.0 and normal colour vision according to Ishihara colour vision Test.

### *Procedure*

For each colour centre, there were 21 conditions (3 colour directions × 7 spatial frequencies) and for each condition, each observer made a forced choice judgement about 40 times. The experiment lasted about 2 hours for each observer (two colour centres). The experiment was divided into 6 sessions, each about 20 minutes (observers took a break of 5 minutes between sessions, they readapted to the background colour for one minute at the beginning of each session). Note that the former 3 sessions for the first colour centre, and the later 3 sessions for the second colour centre. Each colour centre took an observer about 1 hour. The just noticeable difference (JND) or threshold for random conditions were measured. The whole experiment took about 80 hours (8 centres × 10 observers × 1 hour).

Prior to the experiment, the Ishihara vision test was conducted. A written instruction was then given. Observers sat on a chair and used a chin rest to ensure the viewing distance of 60 centimeters. A homogeneous image with the same luminance and chromaticity as the colour centre (background) was shown on the screen. Observers were asked to adapt the background colour for one minute. After the adaptation, a sinusoidal pattern was presented. Observers were asked to press the left or down key on a keyboard when the grating pattern was oriented horizontally or vertically respectively. After the completion of each stimulus, the adaptation image of the background colour was again presented for 1.5 seconds to eliminate the after-image caused by the visual persistence. All the 21 conditions and the direction of grating (horizontal or vertical) were arranged in a random order.

Visible colour difference thresholds were determined using the three-up / one-down weighted stair-case method using a forced choice [18]. The stair-case procedure ended after nine reversal points, about 40 trials of the staircase. The detailed procedure can be found in an earlier publication [19].

## Results

### Inter-observer Variation

Inter-observer variation was investigated by calculating the root-mean square error (RMSE) of contrast sensitivity in logarithmic units ($\log_{10}(S)$) for each frequency at a given colour centre (background). The variation was also given in dB units, calculated by multiplying RMSE by 20. Table 2 lists the inter-observer variation. From Table 2, observers had better consistency for brighter colour centres.

**Table 2: Inter-observer variation**

| | L (cd/m$^2$) | RMSE | dB |
|---|---|---|---|
| WH | 216 | 0.27 | 5.4 |
| WL | 36 | 0.49 | 9.8 |
| RH | 14.1 | 0.63 | 12.6 |
| RL | 7.1 | 0.57 | 11.4 |
| YH | 150 | 0.37 | 7.4 |
| YL | 50 | 0.40 | 8.0 |
| GH | 72 | 0.33 | 6.6 |
| GL | 24 | 0.43 | 8.6 |
| Mean | -- | 0.44 | 8.8 |

### Contrast Sensitivity Results

The contrast threshold values from ten observers for each colour centre were averaged to calculate sensitivity and used in the following analysis.

Figure 2 shows the contrast sensitivity results. From Figure 2 (a), the achromatic channel shows band-pass trend and the peak occurs at a spatial frequency between 0.24 and 0.96 cpd. The R-G and Y-B channels show low-pass trend. Contrast sensitivity decreases with spatial frequency increasing.

Figure 3 shows the scatter plots of the logarithmic contrast sensitivity ($\log_{10}(S)$) for fixed-cycles and fixed-size stimuli at the same spatial frequency. In the present experiment, the fixed-cycles stimuli had two cycles of gratings. But the fixed-size stimuli had between 8 and 204 cycles of gratings as the frequency varied from 0.24 to 6 cpd, respectively. For 0.24 cpd, the logarithmic contrast sensitivity ($\log_{10}(S)$) of the fixed-size (8 cycles) stimuli was 0.3, 0.4 and 0.5 log-10 units larger than the fixed-cycles (2 cycles) for the achromatic, R-G and Y-B channels respectively. For 6 cpd, the logarithmic contrast sensitivity of the fixed-size (204 cycles) stimuli was 0.9, 1.0 and 0.9 larger than the fixed-cycles (2 cycles) for the achromatic, R-G and Y-B channels respectively. For the fixed-cycles stimuli, number of cycles was below the critical value of 4-5 as reported by McCann *et al*. [20] for the detection of sine-wave gratings. Also, contrast sensitivity to be mainly determined by cycle number below the critical value and by spatial frequency above the critical value as reported by Lucassen *et al*. [10].

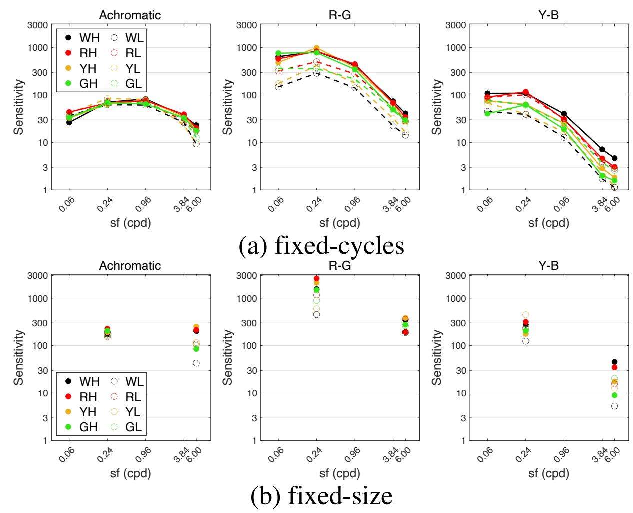


***Figure 2.** Contrast sensitivity results for: (a) fixed-cycles, (b) fixed-size stimuli.*

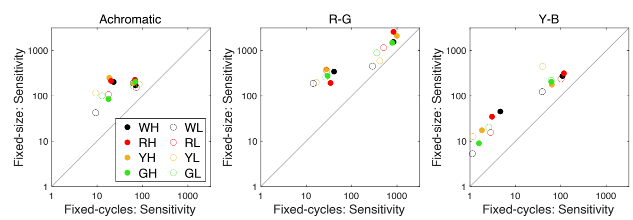


***Figure 3.** Comparison of the logarithmic contrast sensitivity for fixed-cycles and fixed-size stimuli at the same spatial frequency.*

Figure 4 shows the scattering plots of the logarithmic contrast sensitivity for the brighter and darker colour centers having same background chromaticity (the same CIE xy). The contrast sensitivities of the brighter colour centres were slightly larger than those of the darker colour centres. The ratios of luminance levels were 6 (216/36), 2 (14.1/7.1), 3 (150/50) and 3 (72/24) for white, red, yellow and green centres respectively. This verifies Wuerger *et al*.'s [12] finding about contrast sensitivity for a large range of luminance levels, i.e., contrast sensitivity increases with luminance first and reaches the peak at about 200 *cd/m$^2$*, and then decreases (the brightest luminance of the colour centres in the present experiment is 216 *cd/m$^2$*).

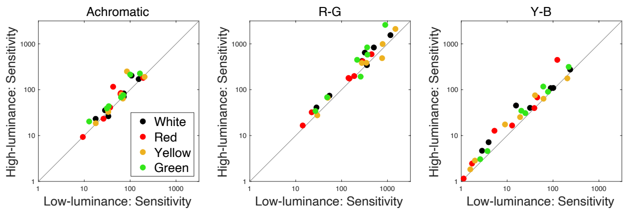


***Figure 4.*** *Comparison of the logarithmic contrast sensitivity for brighter and darker colour centres having the same chromaticity.*

## *Modelling Chromatic CSF*

The contrast sensitivity data were used to fit Mantiuk *et al.*'s [15] cone contrast model. The fitting error was reported as dB, calculated by multiplying the RMSE of contrast sensitivity in logarithmic unit (*log10(S)*) by 20. The loss function is given in equation (12):

$$L = 20 \times \sqrt{\frac{1}{N}\sum_{i=1}^{n}(log_{10}(\tilde{S}_i) - log_{10}(S_i))^2}. \qquad (12)$$

Since the smaller amount of the fixed-size data, only the fixed-cycles data were used to fit the model, i.e., 8 colour centres, 3 colour directions and 5 spatial frequencies.

When the cone contrast model with the original parameters [15] was used to test contrast sensitivity data of the present experiment, the prediction error $L$ was 10.5 dB. The optimized model had a fitting error $L$ of 3.4 dB. Table 3 lists model's error before and after optimization together with inter-observer variation. Figure 5 shows the visual data and the prediction the optimized cone contrast model. Table 4 lists the optimized parameters.

**Table 3: Model's error after (optimized) and before (original) optimization together with Inter-observer variation (Inter) in dB units**

| | L (cd/m$^2$) | Optimized | Original | Inter |
|---|---|---|---|---|
| WH | 216 | 4.4 | 10.0 | 5.4 |
| WL | 36 | 0.2 | 7.6 | 9.8 |
| RH | 14.1 | 3.8 | 12.8 | 12.6 |
| RL | 7.1 | 5.4 | 15.6 | 11.4 |
| YH | 150 | 2.4 | 9.4 | 7.4 |
| YL | 50 | 3.0 | 9.6 | 8.0 |
| GH | 72 | 3.0 | 8.4 | 6.6 |
| GL | 24 | 0.2 | 8.4 | 8.6 |
| Total | -- | 3.4 | 10.5 | 8.8 |

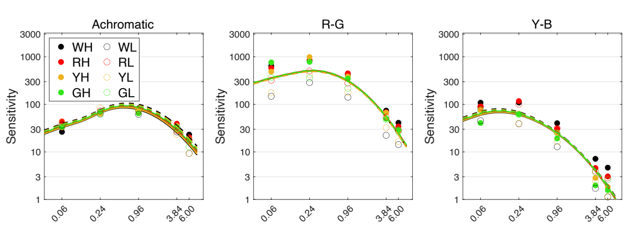


***Figure 5.*** *The visual data and the prediction the optimized cone contrast model.*

**Table 4: Model parameters**

| | |
|---|---|
| $M_{LMS\text{-}ARB}$ | $\begin{bmatrix} 1.000 & 0.190 & 0.038 \\ 1.000 & -1.135 & 0.099 \\ -1.266 & -0.723 & 1.000 \end{bmatrix}$ |
| $p$ | 2.087 |
| $s_{A1}, \ldots, s_{A5}$ | 320.196, 6.883, 0.056, 122883.272, 0.012 |
| $s_{R1}, s_{R2}, s_{R3}$ | 302.898, 6.760, 0.013 |
| $s_{B1}, s_{B2}, s_{B3}$ | 88.636, 23.630, 0.058 |
| $\rho_{A1}, \rho_{A2}, \rho_{A3}$ | 0.716, 3.343, 0.035 |
| $\rho_R, \rho_B$ | 0.182, 0.057 |
| $b_A, b_R, b_R$ | 1.497, 1.931, 1.610 |
| $\gamma_A, \gamma_R, \gamma_B$ | 2.634, 2.634, 2.634 |
| $\hat{a}_A, \hat{a}_R, \hat{a}_B$ | 85.312, 3.367, 3.367 |
| $\hat{f}_A, \hat{f}_R, \hat{f}_B$ | 2.959, 2.634, 2.724 |

## Conclusion

An experiment was conducted to study the contrast sensitivity of different colour directions and spatial frequencies for 4 colour centres, e.g., white, red, yellow and green at two luminance levels for each colour centre. The present data showed a band-passed shape for achromatic chromatic contrast sensitivity function and a low-pass shape for R-G and Y-B contrast sensitivity functions. The fixed-size stimuli (much more than 2 cycles) had larger contrast sensitivities than the fixed-cycles stimuli (fixed 2 cycles). The brighter colour centres had larger contrast sensitivities than the darker ones in the present experiment. The results were used to fit a cone contrast model. The optimized model gave an accurate prediction of contrast sensitivity at different spatial frequencies.

The present experimental results will be added into our earlier datasets [19, 21]. The combined data will be used to develop a more comprehensive model.

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