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Are Spatial Chromatic Contrast Sensitivity Band-pass or Low-pass Functions?

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Abstract

The goal of this research is to generate high quality chromatic Contrast Sensitivity Function (CSF) over a wide range of spatial frequencies from 0.06 to 3.84 cycles per degree (cpd) surrounding 5 CIE proposed colour centres (white, red, yellow, green and blue) to study colour difference. At each centre, 6 colour directions at each of 7 frequencies were sampled, from 0.06 to 3.84 cycles per degree (cpd) corresponding to the number of cycles: from 2.3 to 144.4 respectively. A threshold method based on forced-choice stair-case was adopted to investigate the just noticeable (threshold) colour difference. The results revealed that the chromatic CSF under the present experimental conditions having many lower spatial frequencies covering five colour centres to be band pass, whereas previous results indicated it was low pass. However, this could be caused by the present experimental conditions such as fixed-size stimuli and constant luminance. The new chromatic CSF for R-G and Y-B channels were also developed.

Introduction

The human visual system has different sensitivity to contrast patterns at different spatial frequencies. The function to describe this dependence for simple sinusoidal patterns is called contrast sensitivity function (CSF). The CSF for luminance patterns has been studied extensively and robust models are established. Barten [1] developed two models: one that is a physiologically inspired complex model and the other that is relatively simple and empirically fitted to psychophysical data as given in equation (1).

$$csf(f) = afe^{-bf}\left(1+ce^{bf}\right)^{0.5}, \tag{1}$$

where

$$a = \left[1000p(1)\left(1+\frac{0.7}{L}\right)^{-0.2}\right]/[1+\frac{12\left(1+\frac{f}{3}\right)^{-2}}{w}],$$

$$b = p(2)\left(1+\frac{100}{L}\right)^{0.15},$$

$$c = p(3),$$

and where $p(1)=0.54$, $p(2)=0.3$, $p(3)=0.06$; f is spatial frequency in *cpd* unit; w is the stimulus size in degrees of view angle; L is the mean luminance of the stimulus in cd/m^2.

Unlike luminance CSF, the chromatic CSF depends on the direction of change in an equi-luminance plane, where the direction is defined in some colour spaces [2-10]. Flicker photometry [11] should be done for each individual observer to ensure that the chromatic gratings are iso-luminant for each observer to avoid any contribution from the luminance channel which might interfere with the judgement of the chromatic stimulus.

Since the 1950s, many visual psychophysical experiments have been carried out to investigate chromatic CSF. In 1985, Mullen produced more complete chromatic CSF data [12]. Many researchers investigated red-green and yellow-blue CSF [2, 6–10]. Some investigations also studied lime-purple and cyan-orange gratings [3, 5].

However, investigations to cover a range of colour directions are limited. Vogels *et al*. [4] studied chromatic CSF in 4 evenly distributed colour changing directions in u'v' plane around 3 colour centres at correlated colour temperatures of 2600 *K*, 3800 *K* and 5700 *K*, each at spatial frequencies of 0.15, 0.3, 0.5, 1.5, 3 and 5 *cpd*. They found that contrast threshold had a turning point at spatial frequency of 0.3 *cpd*, which indicated that chromatic CSF data could probably be modelled by band-pass functions.

Johnson and Fairchild [13] introduced luminance, R-G and Y-B models to be used in S-CIELAB [14] to calculate spatial colour difference between images.

The luminance model is shown in equation (2).

$$csf(f) = a\cdot f^{c}\cdot e^{-b\cdot f}, \tag{2}$$

where $a=75$, $b=0.2$ and $c=0.8$.

The R-G and Y-B model is given in equation (3).

$$csf(f) = a_1\cdot e^{b_1\cdot f^{c_1}} + a_2\cdot e^{b_2\cdot f^{c_2}}, \tag{3}$$

where $a_1 = 109.1413$, $b_1 = -0.0004$, $c_1 = 3.4244$, $a_2 = 93.5971$, $b_2 = -0.0037$ and $c_2 = 2.1677$ for R-G channel; or $a_1 = 7.0328$, $b_1 = -0.0000$, $c_1 = 4.2582$, $a_2 = 40.6910$, $b_2 = -0.1039$ and $c_2 = 1.6487$ for Y-B channel.

Figure 1 plots the spectral sensitivity functions of Johnson and Fairchild in log-log axis.

The goal of the present research is to accumulate reliable experimental data and to develop robust chromatic CSFs. A threshold method based on forced-choice stair-case was adopted to assess just noticeable or threshold colour difference in 6 colour changing directions at 7 spatial frequencies. The new colour discrimination ellipses and chromatic CSFs were developed by fitting the data.

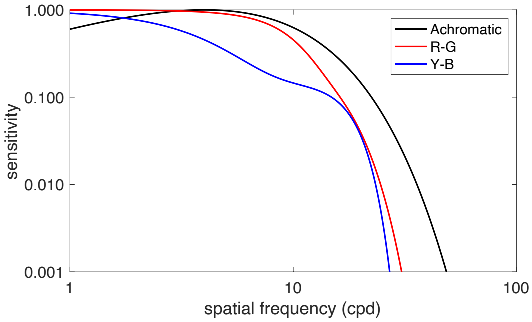

Figure 1. *CSFs in Johnson and Fairchild's work.*

Experiment

Stimulus

The experiment was conducted in a dark room. Spatial chromatic patterns were presented on a 10-bit 'NEC MultiSync PA272W' LCD display with 2560 × 1440 pixels, which was set at a constant peak luminance of 100 cd/m^2 and calibrated using a Gain-Offset-Gamma (GOG) model [15]. The stability of the display was 0.93 ΔE^*_{ab} averaged from measurements of the peak white over a period of six hours at 20-second intervals. The spatial uniformity of the display had a MCDM value (the mean colour difference calculated from a set of mean colour differences) of 1.24 ΔE^*_{ab} units. It was evaluated by equally dividing the display area into 3 × 3 zones. The display was characterized using the GOG model and had a mean prediction accuracy of 0.76 ΔE^*_{ab} from the colour patches of 24 colours on an X-Rite Macbeth ColorChecker chart (MCCC). The measurements for all these characteristics were made using a Konica Minolta CS2000A spectroradiometer. All results were reported for the CIE 1964 standard colorimetric observer. The instrument and display were quite stable over time, i.e. 0.53 ΔE^*_{ab} calculated between the 24 MCCC colour patches at the beginning and at the end of the experiment over a period of three months. 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.

Table 1: Parameters for chromatic CSFs

	u'	v'	L (cd/m^2)
White	0.1979	0.4695	72
Red	0.3155	0.5016	14
Green	0.1449	0.4758	24
Yellow	0.2109	0.5234	50
Blue	0.1700	0.3772	9

The chromaticity varied sinusoidally in CIE 1976 u'v' chromaticity space close to the 5 CIE centres recommended to study colour difference [16], i.e. white, red, green, yellow and blue. Table 1 lists the chromaticity and luminance of the 5 colour centres. The chromaticity was modulated at each of seven spatial frequencies (0.06, 0.12, 0.24, 0.48, 0.96, 1.92 or 3.84 *cpd*) along 6 colour-changing directions (0, 30, 60, 90, 120 and 150 degrees in u' axis) for all centres except the green centre. For green centre, colour changing directions were 0, 40, 70, 100, 120 and 150 degrees in u' axis. These were chosen to give better colour rendering accuracy. Figure 2 shows the colour centres and colour directions. The stimulus size was fixed, and the number of cycles shown on the display were 2.3, 4.5, 9.0, 18.0, 36.1, 72.2 and 144.4 for each spatial frequency respectively.

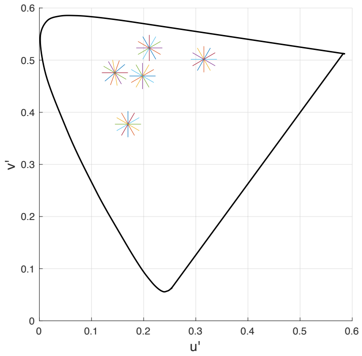

Figure 2. *Colour centres in u'v' space and the colour directions at each of the centres*

The colour difference of the patterns ranged from 0 to 0.013 $\Delta u'v'$ for the white centre and from 0 to 0.033 $\Delta u'v'$ for the other centres. Increasing the colour difference step increased the colour difference size. Each observer viewed the screen from a distance of 50 centimeters and the total field of view (FOV) was 61.5° × 37.6°. The lowest spatial frequency was 0.06 *cpd*, so the -angle of subtense should be large enough to ensure that at least one complete cycle was displayed on the screen. Please note that observers kept their eyes a short distance in front of the screen and the full size of the screen was used to obtain a large angle of subtense.

Figure 3. *Chromatic patterns: horizontal (left); vertical (right)*

Figure 3 shows an example of the chromatic patterns. The chromaticity difference was multiplied with a Gaussian shaped function (with a σ of 37.6°/4) to eliminate the effect of the edges. The background chromaticity of the screen was the same as the base colour of the sinusoidal pattern. The patterns were oriented either horizontally or vertically. It is assumed that both patterns would give the same threshold [10].

Observers

In total, 89 observers took part in the experiment (45 male and 44 female), varying in age from 17 to 29 years, with a mean age of 21.8 (standard deviation is 2.1). Each carried out the experiment between 1 to 5 colour centres. For each colour centre, 20 observers' visual data were measured. In other words, not all observers did all colour centres. 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 42 conditions (6 colour directions × 7 spatial frequencies) and for each condition, each observer made a forced choice judgement about 40 times. The experiment lasted about fifty hours (an average of 2.5 hours for each observer) for each colour centre. The experiment was divided into 6 sessions, each about 20 minutes (observers took a break of 5 minutes between each session). The just noticeable difference (JND) or threshold for random conditions were measured. Before each session, observers took a one-minute adaptation. The whole experiment took about 250 hours (5 centres × 20 observers × 2.5 hours).

Prior to the experiment, the Ishihara vision test was conducted. A written instruction was then given. Observers sat on a chair and kept their eyes 50 centimeters in front of the display. When the experiment started, all other light sources were turned off. Afterwards, a homogeneous image with the same luminance and chromaticity as the base colour was shown on the screen. Observers were asked to look at this image for one minute to become chromatically adapted. 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 (see Fig. 3). After the completion of all stimuli in each colour centre the adaptation image of the base colour was again presented for two seconds to eliminate the after-image caused by the visual persistence. All the 42 conditions and the direction of grating (horizontal or vertical) were arranged in a random order. Note that a chin rest was not used due to uncomfortable for observers to view bright and large field stimuli at the fixed position for quite some time.

Visible colour difference thresholds were determined using the three-up / one-down weighted stair-case method using a forced choice [17]. The detailed procedure can be found in an earlier publication [18].

Results

Spatial chromatic JND Ellipse fitting

As mentioned earlier, a colour centre, includes 6 colour changing directions at each spatial frequency. Twelve thresholds on 6 colour changing directions and their symmetric directions are used to fit an ellipse described by three parameters, *A*, *B* and *θ*, which correspond to the semi-major, semi-minor, and angle, respectively. These can be used to interpret the size, shape (*A*/*B*) and orientation of an ellipse. Each ellipse indicates the threshold changes with different colour directions and spatial frequencies.

For each individual observer, their own ellipses were found to be very consistent. The results showed that inter-observer variability was small, ranged from 0.001 (green) to 0.0007 (white) *Δu'v'* units. This implies that observers were very consistent (small *Δu'v'* units). And observers had higher agreement in white area.

The mean results for the 42 conditions in each centre were obtained from the 20 observers. These were used to fit JND ellipses. Figure 4 shows the visible colour difference thresholds expressed as semi-major axis in Δu'v' unit as a trend of logarithmic spatial frequency in each color changing direction for the 5 colour centres in the present experiment and one colour centre with a correlated colour temperature of 5700 *K* in Vogels *et al*.'s experiment [4]. Error bars indicate 95% CI by averaging different colour changing directions. It can be seen from 0.06 *cpd* to 0.24 *cpd* in the present experiment, human visible colour difference threshold decreases but then increases after 0.24 *cpd*. It can be found that threshold reaches the minimum value at about 0.24 *cpd*, hence it can be concluded that human chromatic contrast sensitivity is at peak at spatial frequency around 0.24 *cpd*. It confirms the results found by Vogels *et al*. In their work, spatial frequencies were set at 0.15, 0.3, 0.5, 1.5, 3 and 5 *cpd*. A similar trend was found and the threshold was found at the minimum at 0.3 *cpd*.

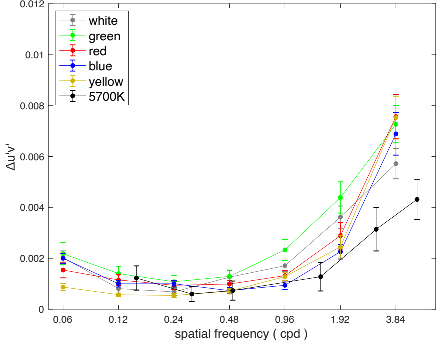

Figure 4. *Visible colour difference thresholds expressed as semi-major axis in Δu'v' unit as a trend of logarithmic spatial frequency. Error bars indicate 95% Confidence interval.*

Figure 4 shows that the minimum thresholds for all colour centres were always located at 0.24 *cpd* and then increased in both directions. In fact, the thresholds at 0.06 *cpd* were close to those at 0.96 *cpd*. It also clearly shows that the threshold values are similar for all colour centres.

The visible colour difference threshold represents the chromatic contrast. The sensitivity is the reciprocal of contrast. In the previous investigations, chromatic CSFs were fitted as low-pass curves, which means visible colour difference threshold increases as spatial frequency increasing. This experiment obtained similar results as previous at spatial frequency greater than 0.48 *cpd*. Nevertheless, chromatic CSF cannot be fitted in the previous investigations because of the shortage of data at low spatial frequency.

Figure 5 shows the JND ellipses of 7 spatial frequencies around 5 colour centres in u'v' plane using the mean JND values of their respective 20 observers. The ellipses were drawn at 5 times size to be seen clearly.

Figure 5 shows a consistent pattern that at high spatial frequencies larger than 0.48 *cpd*, most of the ellipses had quite consistent orientation. The contrast between chromaticity changing along semi-major axis direction had the least strict tolerance and is the most difficult to distinguish. The contrast between chromaticity changing along semi-minor axis direction had the smallest tolerance and is the easiest to distinguish. All sets show that *A*/*B* value increases (ellipse becomes longer) at high spatial frequency. This implies that the nonuniformity is more acceptable at higher spatial frequencies.

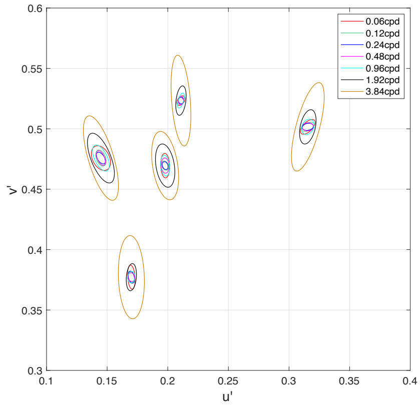

Figure 5. *JND ellipses in u'v' plane (ellipses were drawn as 5 times size)*

By comparing the ellipses in Figure 5, all ellipses had a similar shape with an average *A*/*B* around 2.1 and they all orientated towards in the green/purple direction. Their sizes between different colour centres are differed by a factor of 2, ranged from 7 (yellow) to 14 (green). Comparing the ellipses in different frequencies, those at 0.06 *cpd* had similar size as 0.96 *cpd*. The largest ellipses are always for 3.84 *cpd* as expected.

Modelling Chromatic CSF

Sensitivity was defined as the reciprocal of colour difference, i.e. $1/\Delta u'v'$. Figure 6 shows sensitivity for different spatial frequencies in each individual direction for each individual colour centre plotted with a log ($1/\Delta u'v'$)-log (*cpd*) axis.

Figure 6 shows a band-pass trend, which is quite different from previous investigations. The peak occurs at a spatial frequency of about 0.24 *cpd*.

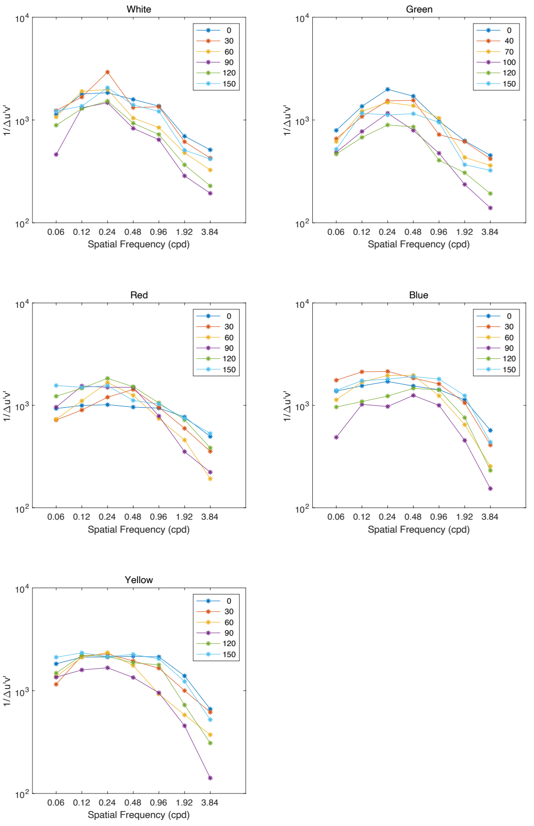

Figure 6. *Sensitivity as a trend of spatial frequency in log-log axis*

The 0° and 90° from u' axis for each centre were selected to represent the Red-Green and Yellow-Blue CSFs. Firstly, Johnson and Fairchild's chromatic CSFs (equations 3) were used to fit the experimental data by minimizing the root-mean square error (RMSE) between the visual data and models' predictions. However, the models did not fit well due to the band-pass nature of the data. So, the luminance CSF [13] (equation 2) was used to fit the data as shown in Figure 7. Their coefficients, *a*, *b* and *c* can be optimised from the present experimental data. In addition, Barten's luminance model [1] was also employed. Equation 1 shows the model, and the variable coefficients, *p(1)*, *p(2)* and *p(3)* can be fit to the present experimental data.

Again, RMSE calculated between the psychophysical data and the predictions of contrast sensitivity was minimized to obtain the coefficients in equations 1 and 2. For equation 1, the mean luminance parameter *L* of each individual colour centre was used and the experimental data from all 5 colour centres were combined to minimize the RMSE value. For equation 2, experimental data from all 5 colour centres were combined in the minimization process. Figure 7 shows the fitting results of Equation 1 and 2 plotted in log-log axis, and Table 2 lists their optimised coefficients and RMSE values.

Table 2: Optimised coefficients and RMSE values of combined data

		a	*b*	*c*	RMSE
Equation 1	R-G	19.40	2.58	0.16	1525
	Y-B	18.61	3.42	0.15	1058
		p(1)	*p(2)*	*p(3)*	RMSE
Equation 2	R-G	2383.49	-0.52	0.19	363
	Y-B	3482.53	-1.48	0.45	266

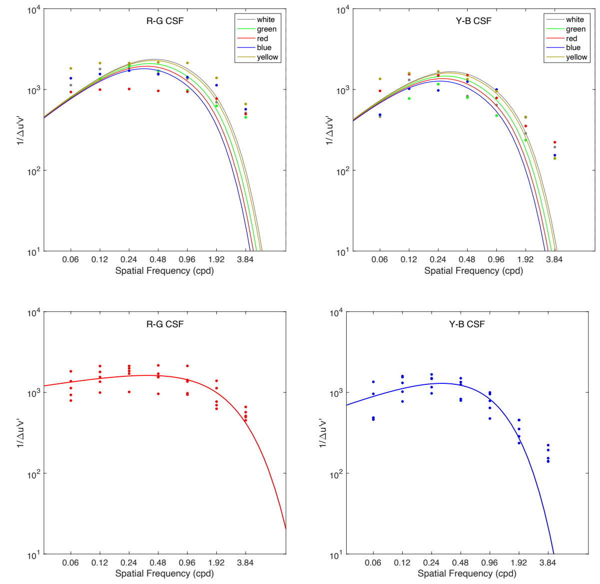

Figure 7. *Sensitivity functions of Equation 1 (R-G on the top left, Y-B on the top right) and 2 (R-G on the bottom left, Y-B on the bottom right) in log-log axis*

The results clearly showed that Johnson and Fairchild's model (Equation 2) outperformed Barten's model (Equation 1). And the chromatic CSFs indicate a band-pass shape, contrasting with the previous assumption of a low-pass shape.

Note that a possible reason to cause this discrepancy is the interference of the luminance signal [11], i.e. the chromatic gratings were set to constant CIE luminance in the present experiment, but the true iso-luminant point may vary for each observer. In other words, for individual observers, the chromatic gratings may have carried a small luminance component. However, Lucassen *et al.* [19] stated otherwise, the iso-luminant for the lower spatial frequencies they studied was likely to be small, because the achromatic contrast sensitivity is negligibly small relative to chromatic contrast sensitivity. The present results including many low frequencies data surrounding different colour centres may be sufficient to prove the band-pass nature of chromatic CSFs found here.

Furthermore, because of the fixed size of the stimulus on the display, the number of cycles shown was limited at very low spatial frequency. This could also affect the sensitivity of detection. For a spatial frequency of 0.06 *cpd*, number of cycles was below the critical value of 4-5 as reported for the detection of sine-wave gratings [20]. As reported by Lucassen *et al.* [19], contrast sensitivity is mainly determined by cycle number below the critical value and by spatial frequency above the critical value.

Conclusion

An experiment was conducted to study the perceptibility of chromatic contrast threshold of different colour directions and spatial frequencies for 5 colour centres, e.g. white, green, red, blue and yellow. The results were used to fit just noticeable colour difference functions and JND ellipses. The minimum threshold was found at the spatial frequency of 0.24 *cpd*. This indicates that chromatic contrast sensitivity reaches the peak at about 0.24 *cpd*. The results confirmed with the previous finding from Vogel *et al*. It was also found that JND thresholds performs differently along different colour changing directions. For high spatial frequencies, uniformity of colour space decreases.

The present data showed a band-passed shape for spatial chromatic contrast sensitivity functions under the present experimental conditions. However, this could be caused by the setting of experimental conditions, i.e. fixed-size stimuli and constant luminance. Individual iso-luminant stimuli and limited number of cycles may have a little impact on the sensitivity of detection. Further work will be carried out to consider to explore these conditions.

Acknowledgement

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