https://doi.org/10.2352/issn.2694-118X.2020.LIM-31

Investigation of Spatial Chromatic Contrast around 5 Colour Centres

***Qiang Xu*[1], *M. Ronnier Luo**[1], *Dragan Sekulovski*[2]**
[1]State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou, China
[2]Philips Lighting Research, Eindhoven, The Netherlands
Corresponding Author: M.R.Luo@zju.edu.cn

Abstract

The goal of this research work is to generate high quality chromatic contrast sensitivity (CCS) data over a large range, especially at low spatial frequencies surrounding 5 colour centres, e.g. white, red, yellow, green and blue. An experiment was carried out using forced-choice stair-case method to investigate the visible colour difference thresholds in different colour changing directions at different spatial frequencies. The just noticeable difference (JND) ellipses at different spatial frequencies were used to represent the data.

Introduction

With the rapid development in the lighting and imaging industries, standard comprehensive models for the visual perception of chromatic nonuniformities are urgently required.

Human visual system has different perception for contrast patterns at different spatial frequencies. The function describing this dependence for simple sinusoidal patterns is called a contrast sensitivity function (CSF). The CSF for luminance patterns were studied extensively and robust models were established [1]. Unlike luminance CSF, chromatic contrast sensitivity additionally depends on the direction of change in an equiluminance plane, where the direction is defined in some colour spaces. This research work has been limited to develop a comprehensive CCS function.

Light Emitting Diode (LED) technology offers many new opportunities for the lighting industries. However, LED luminaires, depending on the design, have chromaticity nonuniformity at very different spatial frequencies. Differences between luminaires are typically low frequency with little overlap between the beams, while the nonuniformities within one luminaire are typically a mix of several higher frequencies. The industry standard measures of colour differences are based on a fixed geometry and do not take frequency into account [2]. To build new models that include spatial frequency, more studies on CCS are urgently needed. The CCS is also valuable in imaging field, image quality can be improved using better models that include spatial frequency dependence.

Since the 1950s, lots of visual psychophysical experiments have been carried out to investigate CSF. Until 1985, Mullen provided relatively complete CSF data [1]. In recent years, displays replaced traditional optical systems to generate test patterns [3-16]. Many researchers investigated red-green and yellow-blue CSF [7-9]. Besides, a few investigations studied lime-purple and cyan-orange gratings [5,10]. However, investigations about chromaticity varying in other colour directions are limited. Lv *et al.* recruited 6 observers and studied CCS in 6 colour changing directions in a^*b^* plane (0, 45, 67.5, 90, 112.5 and 135 degrees with a^* axis) around a grey centre (L^*=76, a^*=b^*=0) and a red centre (L^*=44, a^*=37, b^*=23), at spatial frequencies at 0.5, 1, 2.6, 5.2, 7.8 and 11.7 cycles/deg (cpd) [5]. Vogels *et al.* recruited 18 observers and studied CCS in 4 evenly distributed colour changing directions in u'v' plane around 3 colour centres with a correlated colour temperature of 2600K, 3800 K and 5700K, at spatial frequencies at 0.15, 0.3, 5.0, 1,5, 3 and 5 cpd [2, 3]. This paper introduces a CCS investigation around 5 colour centres over a wide range, especially at low spatial frequencies.

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 GOG model.

The chromaticity varied sinusoidally in CIE 1976 u'v' chromaticity space close to the 5 CIE centres, i.e. white (u' = 0.1979, v' = 0.4695, luminance = 72 cd/m^2), green (u' = 0.1449, v' = 0.4758, luminance = 24 cd/m^2), red (u' = 0.3155, v' = 0.5016, luminance = 14.1 cd/m^2), blue (u' = 0.1700, v' = 0.3772, luminance = 8.8 cd/m^2) and yellow (u' = 0.2109, v' = 0.5234, luminance = 50 cd/m^2). The chromaticity was modulated at 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 for better colour rendering accuracy.

The colour difference of the patterns ranged from 0 to 0.013 Δu'v' for white centre and from 0 to 0.033 Δu'v' for the other centres. The colour difference step was changing with the colour difference size, large steps for large Δu'v' size and small steps for small Δu'v' size. Each observer's eyes were 50 centimeters away from the screen and the total viewing field was 61.5° × 37.6°.

Figure 1 shows the examples of two chromatic patterns. The chromaticity difference was multiplied with a Gaussian shaped function (37.6° × 37.6°) 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. Human visual system has almost the same perception of horizontal and vertical patterns [17].

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 did 1 to 5 colour centres. For each colour centre, 20 observers' visual data were measured. All observers had a normal visual acuity of 1.0 and normal colour vision.

(a)

(b)

Figure 1. *Chromatic patterns: (a) horizontal; (b) vertical*

Procedure

For each colour centre, 6 colour changing directions and 7 spatial frequencies were used. In total, there are 42 conditions. For each condition, one single observer made a forced choice judgement about 40 times. The whole experiment lasted about fifty hours (in average 2.5 hours for each observer). The experiment was divided into 6 sessions, each about 20 minutes. Observers then took a break of 5 minutes between two sessions. The visible CCS thresholds for random conditions were measured. The whole experiment took about 250 hours (5 centres × 20 observers × 2.5 hours).

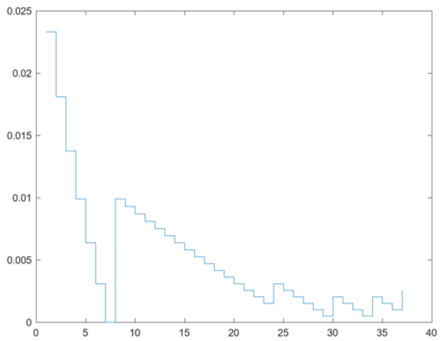

Figure 2. *An example of staircase. The horizontal axis is the number of trials, and the vertical axis is the colour difference in Δu'v' unit*

Prior to the experiment, Ishihara vision test was conducted. The 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. After each stimulus the adaptation image of the base colour was 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.

Figure 2 shows an example of staircase. Visible colour difference thresholds were determined using the three up/ one down weighted stair-case method using a forced choice [18]. The first pattern had a maximum colour difference, which was clearly visible to all observers. The modulation presented next depended on the response to the preceding pattern. If observers made the right choice (they correctly indicated the horizontal or vertical direction of the pattern), the colour difference (Δu'v') would reduce to the next step. Otherwise, the colour difference would increase to three steps upward. This difference in step sizes ensures that the procedure converges to the 75% correct point, further corresponding to the 50% detection point, or the JND. The observers were instructed to make random choices when they could not judge the orientation of the patterns at a certain colour difference. During the procedure, the colour difference would fluctuate near the threshold. For each condition, the stair-case procedure ended after nine turning points of the staircase.

Results & Discussion

For each colour centre, each spatial frequency includes 6 colour changing directions. 12 thresholds on 6 colour changing directions and their centrosymmetric directions are used to fit ellipse. Figure 3 shows an example of ellipse fitting. Each ellipse is described by 5 parameters, *A*, *B*, *A/B*, *θ* and *area*, which correspond to the semi-major, semi-minor, shape, orientation and size of an ellipse, respectively. Each ellipse indicates the threshold changes with different colour directions and spatial frequencies.

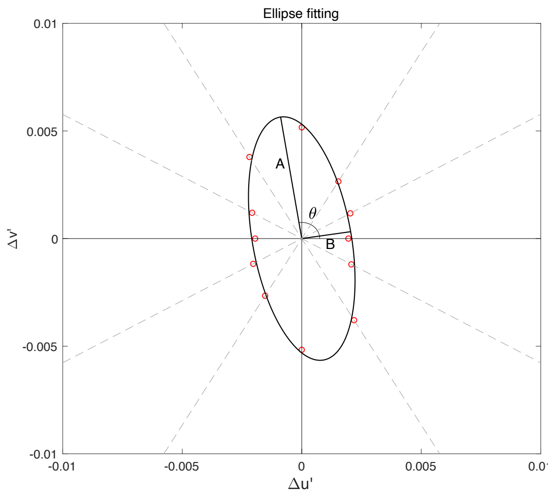

Figure 3. *An example of ellipse fitting*

For each individual observer, their own ellipses were found to be very similar. The results showed that inter-observer variability was small, ranged from 0.0007 (white) to 0.001 (green) in Δu'v' unit. For normal colour vision observers, they had different chromatic acuity from each other, but the difference is small.

The results for the 42 conditions were obtained based on the mean results of 20 observers. And the mean results were used to fit ellipses.

Figure 4 shows the visible colour difference thresholds expressed as semi-major axis in Δu'v' unit as a trend of 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 5700K in Voels *et al.*'s experiment [2, 3]. Error bars indicate 95% CI by averaging different colour changing directions. Figure 5 shows the results expressed as a trend of logarithmic spatial frequency. 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.

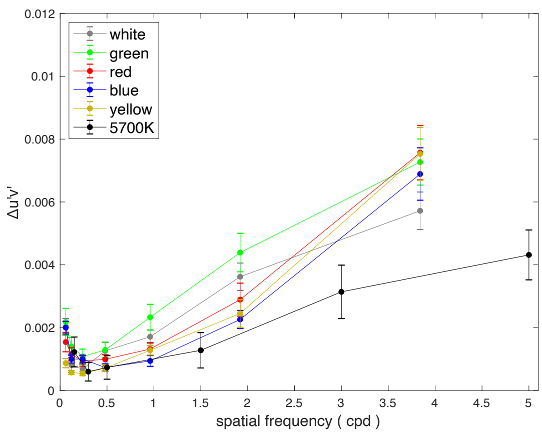

Figure 4. *Visible colour difference thresholds expressed as semi-major axis in Δu'v' unit as a trend of spatial frequency. Error bars indicate 95% CI*

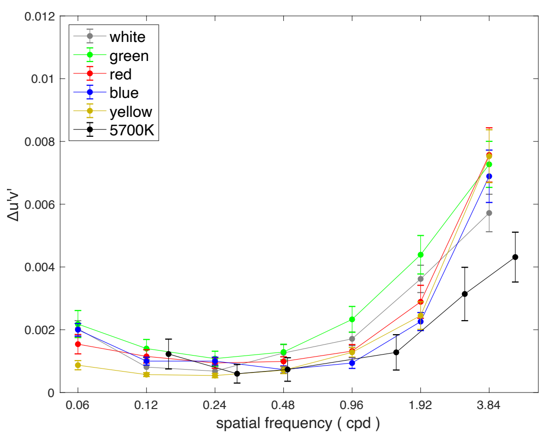

Figure 5. *Visible colour difference thresholds expressed as semi-major axis in Δu'v' unit as a trend of logarithmic spatial frequency. Error bars indicate 95% CI*

Figure 5 showed 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, CCS functions 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.

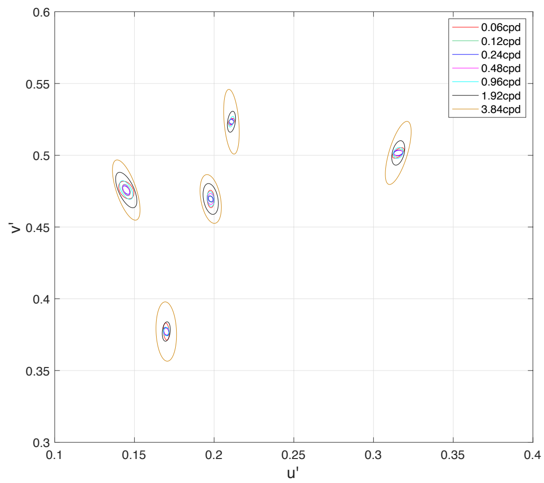

Figure 6. *JND ellipses in u'v' plane (ellipses were drawn as triple size)*

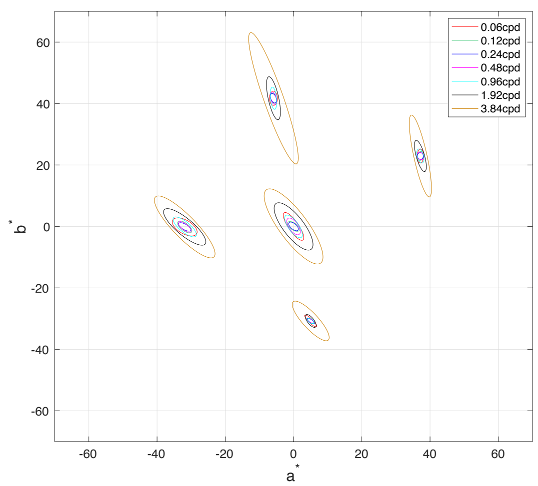

Figure 7. *JND ellipses in CIELAB a*b* plane (ellipses were drawn as triple size)*

Figure 6 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 as triple size to be seen clearly.

The original u'v' data were also transformed into CIELAB colour space and fitted as ellipses in a^*b^* plane. Figure 7 shows the JND ellipses of 7 spatial frequencies around 5 colour centres in a^*b^* plane. The ellipses were drawn as triple size as well.

A large visible colour difference threshold value represents small sensitivity, i.e. a large size of ellipse. When *A/B* is small (the ellipse is close to a circle), this indicates that visible CCS had little variation in different colour directions.

Figures 6 and 7 showed that at high spatial frequencies larger than 0.48 cpd, most of the ellipse 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 satisfying at high spatial frequency.

Figure 6 shows that for threshold ellipses in u'v' plane, all ellipses had a similar shape, (*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, it can be seen that those at 0.06 cpd had similar size as 0.96 cpd. The largest ellipses are always for 3.84 cpd as expected.

Figure 7 shows that for threshold ellipses in CIELAB a^*b^* plane, all ellipses had a similar shape, (*A/B* ranged from 2.7 to 3.6) and they all orientated from red/blue (magenta) to yellow/green direction. The sizes between different colour centres differed by a factor of 5, and ranged from 1.28 (blue) to 5.61 (white). Comparing the ellipses in different frequencies, the results are similar to that in u'v' plane, i.e. those at 0.06 cpd had similar size as 0.96 cpd. The largest ellipses are always for 3.84 cpd as expected.

Conclusion

An experiment was conducted to study the perceptibility of CCS 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 visible colour difference threshold curves 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. JND performs differently along different colour changing directions. For high spatial frequencies, uniformity of colour space decreases. The results can provide a theoretical basis for a model to be used in the lighting and imaging industries.

Acknowledgement

The authors like to thank the support from the Chinese Government's National Science Foundation (Project Number on 61775190).

References

[1] K.T. Mullen. The contrast sensitivity of human color vision to red-green and blue-yellow chromatic gratings. Journal of Physiology, 1985, 359(1): 381.

[2] I.M. Vogels, M. Lambooij. Visibility of spatial chromatic contrast for lighting applications. Experiencing Lighting 2014.

[3] M. Lucassen, M. Lambooij, D. Sekulovski, *et al*. Spatio-chromatic sensitivity explained by post-receptoral contrast. Journal of Vision (2018) 18(5):13, 1–18.

[4] Z. Wang, H. Xu. Investigations of suprathreshold color-difference tolerances with different visual scales and different perceptual correlates using CRT colors. Optical Society of America. Journal A: Optics, Image Science, and Vision, 2008, 25(12).

[5] W. Lv, H. Xu, Z. Wang, M.R. Luo. Investigation of chromatic contrast sensitivity based on different color directions and spatial frequencies. Acta Optica Sinica, 2011, 31 (01): 301-306.

[6] J. Shi, J. Yao, H. Yu, L. Yun. Measurement of luminance contrast sensitivity function of human visual system on cathode ray tube display. Acta Optica Sinica, 2007, (04): 744-748.

[7] S. Wuerger, M. Ashraf, M. Kim, *et al*. Spatio-chromatic contrast sensitivity under mesopic and photopic light levels. Journal of Vision, in print. (2020).

[8] K. J. Kim, R. Mantiuk, K. H. Lee. Measurements of achromatic and chromatic contrast sensitivity functions for an extended range of adaptation luminance. In B. E. Rogowitz, T. N. Pappas, & H. de Ridder (Eds.), Human Vision and Electronic Imaging (p. 86511A). (2013).

[9] S.M. Wuerger, A.B. Watson, A. Ahumada. Towards a spatio-chromatic standard observer for detection. In B. E. Rogowitz & T. N. Pappas (Eds.), Proceedings of the SPIE: HVEI (Vol. 4662, pp. 159–172). (2002).

[10] H.C. Owens, S. Westland, V.K. Van, et al. Contrast sensitivity for lime-purple and cyan-orange gratings. Color and Imaging Conference. 2002: 145-148.

[11] W. Lv, H. Xu, Z. Wang, M.R. Luo. Contrast sensitivity function based on color difference under different fields. The Chinese Optical Society. 2010:8.

[12] S.M. Wuerger, M.J. Morgan, S. Westland, et al. The spatio-chromatic sensitivity of the human visual system. Physiological Measurement, 2000, 21(4).

[13] J.M. Rovamo, M.I. Kankaanpää, J. Hallikainen. Spatial neural modulation transfer function of human foveal visual system for equiluminous chromatic gratings. Vision Research, 2001, 41(13).

[14] J.M. Rovamo, M.I. Kankaanpää, H. Kukkonen. Modelling spatial contrast sensitivity functions for chromatic and luminance-modulated gratings. Vision Research, 1999, 39(14).

[15] S. Kitaguchi, L. Macdonald, S. Westland. Evaluating contrast sensitivity. Electronic Imaging. International Society for Optics and Photonics, 2006: 605704-605704-10.

[16] P.J. Seuntiens, I.M. Vogels, D. Sekulovski, et al. Visibility of color differences in LEDs. AIC Color Special symposium: LED Lighting, Newcastle Gateshead, UK, 2013

[17] S.A. Rajala, H.J. Trussell, & B. Krishnakumar. Visual sensitivity to color-varying stimuli. Proceedings of SPIE - The International Society for Optical Engineering, 1666, 375-386. (1992).

[18] C. Kaernbach, Simple adaptive testing with the weighted up-down method, Perception & Psychophysics, 1991, 49, 227-229.

Author Biography

Qiang Xu received his BS in Optical Engineering from Zhejiang University in June 2018 and he is now a Master student supervised by Professor Ming Ronnier Luo at Zhejiang University in September 2018. His research work is on colour difference under HDR luminance range and determination of contrast sensitivity function at different colour centres.