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A Study of Visible Chromatic Contrast Threshold Based on Different Color Directions and Spatial Frequencies

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Abstract

The goal of this work is to provide a guideline to produce high quality chromatic contrast sensitivity (CCS) data at low frequencies, and to contrast with the previously published data. An experiment was carried out using forced-choice stair-case method to investigate the CCS just noticeable difference (JND) in different color changing directions at different spatial frequencies. The JND ellipses at different spatial frequencies were fitted and compared with those earlier studies. The results from a white and a green center were reported. They provided theoretical basis and standard practice for the lighting and the imaging industries.

Introduction

Understanding the dependence of contrast patterns on their spatial frequencies provides a basis for developing models of human vision. The function describing this dependence for simple sinusoidal patterns is called a contrast sensitivity function (CSF). The CSF for luminance patterns has been studied extensively and robust models have been established [1,2]. Unlike luminance CSF, chromatic contrast sensitivity additionally depends on the direction of change in an equiluminant plane, where we can define direction in some color space. This additionally increases the parameter space of a potential model and together with the limited research that has been done on the topic leads to a comprehensive CCS function being still in the process of development.

With the rapid growth in the lighting and the imaging industries, standard comprehensive models for the visual perception of chromatic nonuniformities are urgently required. Light Emitting Diode (LED) technology has been rapidly developing in recent years and offers many new opportunities for the lighting industry. Lighting manufacturers use LEDs to create new luminaire designs and to manufacture new products, which are comparatively environmentally friendly and spend considerably less energy compared to traditional light sources. However, LED luminaires, depending on the design, can produce large color nonuniformities in the environment. The root cause of the problem are the inherent variations in dye chromaticity, phosphor thickness, and lumen output in the production process of LEDs. Though LED luminaires can mix the light of individual LEDs through a special optics to make the color variation not perceivable, this usually comes at increased size and cost. Furthermore, color differences can still be observed between luminaires with the same color specs [1,16,18]. These use cases, however, have chromaticity nonuniformities 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. At the same time, the industry standard measures of color differences are based on a fixed geometry and do not take frequency into account.

As a bridge towards models that include frequency, more studies on CCS are urgently needed. This need is not only limited to the field of illumination. In imaging, building better models that include spatial frequency dependence, can be used to improve image quality.

Human visual CCS function data is measured using visual psychophysical experiments. Since the 1950s, many researchers have been working on developing measurement methods to build luminance and CCS functions. Until 1985, Mullen [6] had studied CCS function in detail and gave relatively complete contrast sensitivity function data. After that, the study of contrast sensitivity function data came to an end. Conventional contrast sensitivity testing methods use optical systems to produce the test patterns. These systems are complex and difficult to manipulate. In recent years, with the development of computer technology, displays have become an important part of visual information in our daily life and have been increasingly used for measuring human visual contrast sensitivity.

Many parameters could affect the CCS function, such as the part of the color space (color center), the direction of change of the color (color direction), luminance, and the spatial frequency. Most of the previous investigations about CCSF were in the directions of red-green and yellow-blue [6-9]. There were a few to research lime-purple and cyan-orange directions [10]. Besides, few investigations researched the spatial frequency below 0.2 cycles per degree [1, 4-15]. However, the chromaticity can vary in any direction (not only along red-green or blue-yellow), in any regular or irregular way and ranges from low frequency variations between spots to high frequency variations for wall-washers and in color spots [1]. In order to define more accurate guidelines for the color consistency of LED lighting devices, a new measure has to be developed to quantify the visibility of chromatic contrast for any type of chromaticity variation in a light beam. In previous research, the selection of color directions means that data cannot accurately be fit using a visible chromatic contrast threshold ellipse [1, 6, 7, 9, 10] and visual results of spatial frequency below 0.2 cycles per degree are lacking [1, 4-15]. Furthermore, almost all the previous experiments used few observers (typically six to ten), making the estimation of the accuracy of the data and the interobserver variability hard [1,5,18]. This paper introduces an experiment for studying CCSF with goals of providing a guideline to produce high quality chromatic contrast sensitivity (CCS) data, and comparing with the previously published datasets. In the experiment, 20 observers took part to assess visible

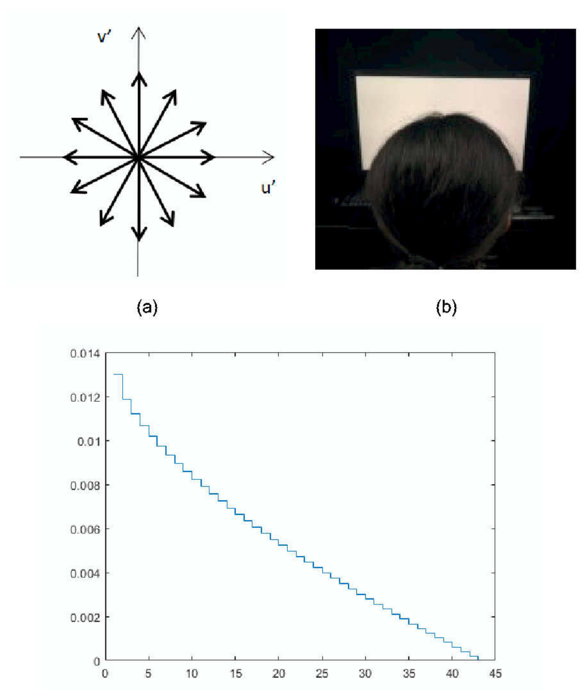
CCS thresholds in six color changing directions and at seven spatial frequencies, for two color centers. The visual results were used to fit color-difference JND ellipses and to compare the performance of CCSF in different color changing directions.

Experiment

Chromatic patterns

The experiment was conducted in a dark room. Spatial chromatic patterns were presented on a 10-bit 'NEC' LCD display with 2560 × 1440 pixels, which was calibrated using a GOG model. The chromaticity varied sinusoidally in CIE 1976 u'v' chromaticity space at a constant luminance of 72 cd/m^2. In the pilots the authors did not detect a possible contribution of luminance to the results that could arise due to individual differences in luminance perception. As a result, no personalized equiluminance was used. The experiment was divided in two main parts for the two color centers. We present and discuss the results for the first color center first.

The color center corresponds to u' and v' of 0.1979 and 0.4695, respectively. The chromaticity was modulated at a base color, white of D65, at seven spatial frequencies (0.06, 0.12, 0.24, 0.48, 0.96, 1.92 or 3.84 cycles per degree) along six color changing directions (0, 30, 60, 90, 120, 150 degrees with u' axis) (Figure 1a). The color difference of the patterns ranged from 0 to 0.013 Δu'v'. The color difference step was changing with the color difference size. Figure 1c shows a series of Δu'v' created, with large steps for large Δu'v' size and small steps for small Δu'v'. Observers' eyes were 50 centimeters away from the screen and the total viewing angle was 37.6 degrees (Figure 1b).

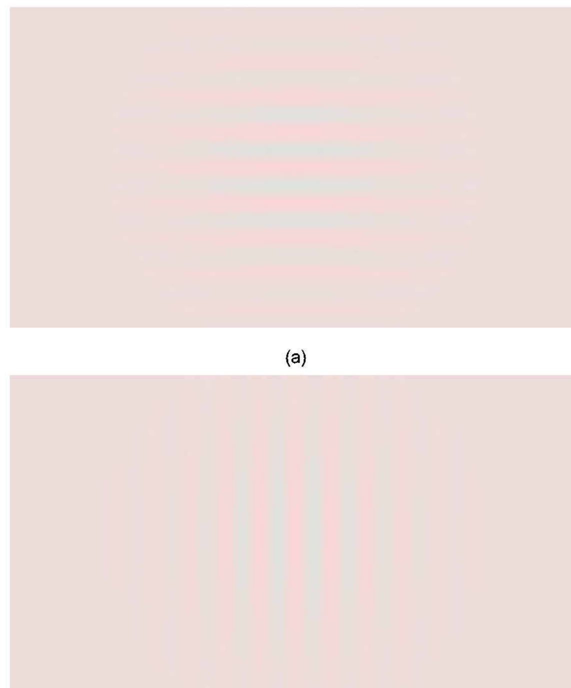


(a) (b)

(c)

Figure 1. Experiment setting. (a) The six color changing directions in CIE 1976 u'v' chromaticity diagram; (b) The experiment situation; (c)A series of color-difference size (Δu'v') in CIE 1976 u'v' chromaticity diagram.

The chromaticity difference was multiplied with a Gaussian shaped function to eliminate the effect of the edges. The background chromaticity of the screen was the same as the base color of the sinusoidal pattern. The pattern could be oriented either horizontally or vertically as shown in Figure 2.



(a)

(b)

Figure 2. Chromatic patterns: (a) An example of the horizontal patterns; (b) An example of the vertical patterns.

Observers

Eleven females and nine males, participated in the experiment. Their ages ranged from 18 to 25 years. All observers had a normal or corrected to normal visual acuity of 1.0 (as tested with the Landolt-C test) and normal color vision (as tested with the Ishihara color-blindness test).

Procedure

As mentioned earlier, 6 color changing directions and 7 spatial frequencies were used. So, each observer assessed 42 conditions in total. For each condition, one single observer made a forced choice judgement about 40 times. The whole experiment lasted about fifty hours (about 2.2-2.7 hours for each observer). The experiment was divided into six sessions of about 20 minutes. In each session, the visible CCS thresholds for 7 random conditions were measured. Prior to the experiment, vision tests were conducted. After that, the written instruction was given and questions about the experimental procedure were answered. Observers sat on a chair and kept their eyes fifty centimeters in front of the display. Each session started with dark adaptation for two minutes. For the dark adaptation, all light sources were turned off. Afterwards, a homogeneous image with the same luminance and chromaticity as the base color of D65 white was shown on the screen. Observers had to look at this image for one minute to become chromatically adapted. After the adaptation, a sinusoidal pattern was presented. Observers had to press the left or right key on a keyboard when the grating pattern was oriented horizontally and the up key or down key when the grating pattern was oriented vertically. After each stimulus the adaptation image of the base color 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.

Visible CCS thresholds were determined using the three up/one down weighted staircase method using a forced choice [17]. The first pattern had a maximum color difference of 0.013 Δu'v', which was clearly visible to most 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 color difference (Δu'v') would reduce to the next step. Otherwise, the color difference would increase to three steps upward. This difference in step sizes insures 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 were made when they could not judge the orientation of the patterns at a certain color difference. During the procedure, the color difference would fluctuate around the visible CCS threshold as shown in Figure 3. For each condition, the stair-case procedure ended after nine turning points of the staircase. The average of the last four turning points was computed as the visible chromatic contrast threshold.

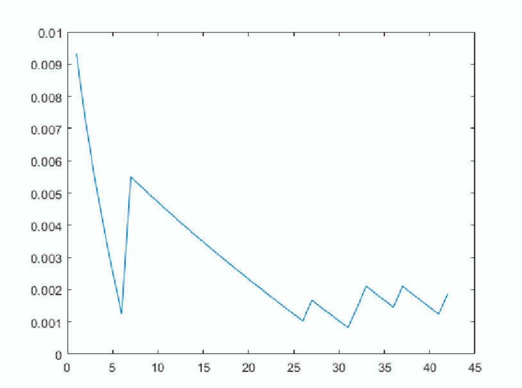


Figure 3. *An example staircase.*

Results & Discussion

Visible chromatic contrast threshold ellipses

The results for the 42 conditions were obtained based on the results of 20 observers. Figure 4 shows the visible CCS JND ellipses of 7 spatial frequencies using the mean JND value from all observers. For different observers, their ellipses could be quite different. But for the same spatial frequency, the sizes, expressed by A (semi-long axis), shape by A/B (ratio of the long and short axes) and orientation by θ (departure from x axis) of all their ellipses are very similar. That is to say, normal color vision observers have different chromatic acuity from each other, but the difference is small. Each ellipse indicates the threshold changes with different color direction and spatial frequency.

The present results were used to compare three different datasets using about the same color center. Our pilot study had similar experimental setting, including the same color changing directions, the same color center at D65 and 1931 colorimetric observer, with similar stimuli and similar spatial frequencies. Figure 5 shows the ellipses, which had good agreement with the present ellipses. Table 1 gives the ellipse parameters from two experiments.

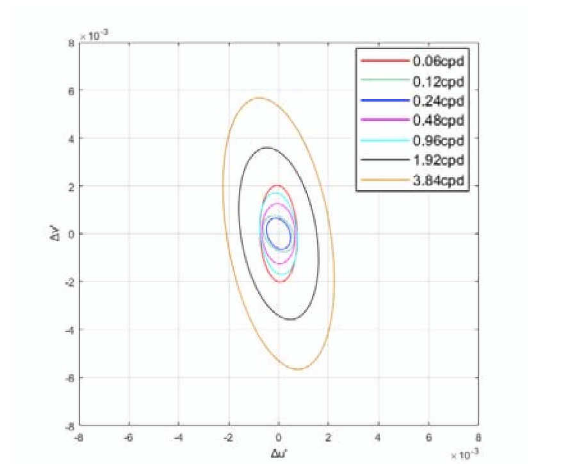


Figure 4. *Visible chromatic contrast threshold ellipses of 7 spatial frequencies.*

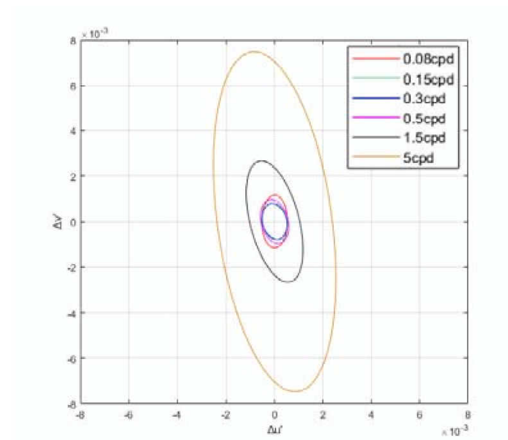


Figure 5. *Visible chromatic contrast threshold ellipses of the pilot experiment.*

Ellipse orientations of the two experiments are close. From 0.06 cpd to 0.24 cpd in this experiment, 'A' decreases but then increases after 0.24 cpd. From the pilot study, 'A' decreases from 0.08 cpd to 0.3 cpd but increases from 0.3 cpd to 5cpd. This implies an excellent agreement between the two. Table 1 results also suggest that visible CCSF decreases and then increases with an increase of spatial frequency. When 'A' is on the small size, 'A/B' is small as well (fatter), which indicates that visible CCS threshold varies slightly in different color changing directions. Comparing two sets of parameters, it can be seen that threshold reaches the minimum value at about 0.24 cpd, hence we can draw conclusion that human chromatic contrast sensitivity is at peak at spatial frequency around 0.24 cpd.

Table 1. Parameters of visible chromatic contrast threshold ellipses in u'v' chromaticity diagram

The present experiment				The pilot experiment			
SF(cpd)	A(10^{-3})	A/B	θ(°)	SF(cpd)	A(10^{-3})	A/B	θ(°)
0.06	2.03	2.72	92.11	0.08	1.16	2.20	89.65
0.12	0.81	1.46	118.82	0.15	0.84	1.61	111.79
0.24	0.68	1.51	110.36	0.30	0.80	1.59	99.95
0.48	1.26	1.89	93.15	0.50	0.97	1.73	102.79
0.96	1.71	2.32	95.76	1.50	2.73	2.69	103.45
1.92	3.62	2.40	99.03	5.00	7.53	3.18	97.17
3.84	5.72	2.76	98.91	-	-	-	-

The second comparison was made to Vogels *et al.*'s [1] which studied at a white color center with a correlated color temperature (CCT) of 5700K. Figure 6 shows their CCS JND ellipses. The ellipse parameters are a little different from those of present experiment. This may be caused by the different color centers used in two experiments (5700K vs D65). But they have something in common, i.e. with an increase of spatial frequency, visible threshold first decreases and then increases.

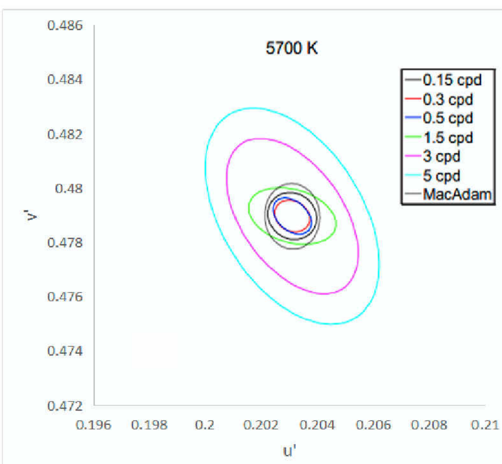


***Figure 6.** Visible chromatic contrast threshold ellipses in the experiment of Vogels et al.*

The final comparison was made against those with Lv *et al.*'s data [5]. Our u'v' data were transformed into CIELAB a*b* in order to compare with theirs. Figure 7 shows our ellipses in a*b* plane and Table 2 also lists the ellipses parameters. It can be seen that for the ellipses having similar spatial frequency, such as 0.48 cpd of this experiment and 0.50 cpd of Lv *et al.*'s, 0.96 cpd of this experiment and 1.0 cpd of Lv *et al.*'s, the 'A', 'A/B' and 'θ' were very similar. In this experiment, from 0.48 to 3.84 cpd, 'A' and 'A/B' values increase (ellipse becomes bigger and longer), but 'θ' maintains a stable value close to 120°. Lv *et al.*'s parameters had the same trend as ours. However, at low spatial frequency less than 0.24 cpd, 'A' value increases (ellipse becomes bigger) with a reduction of spatial frequency.

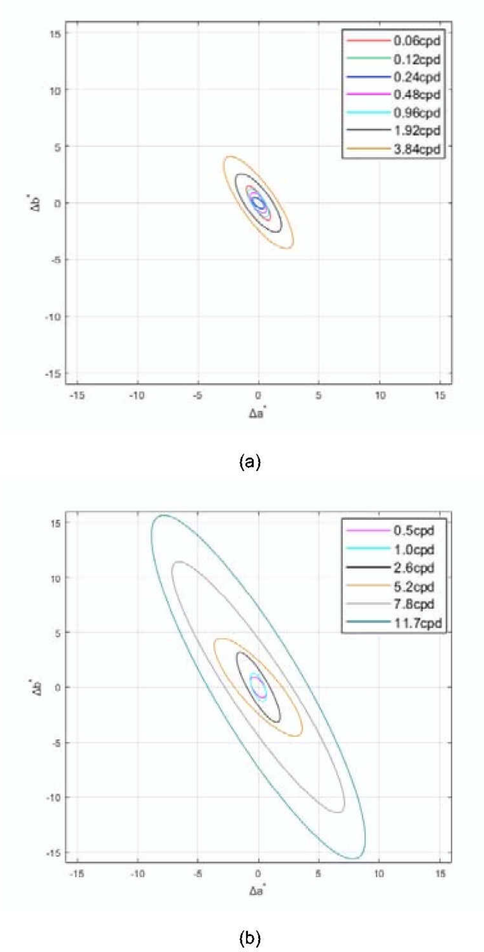


***Figure 7.** Visible chromatic contrast threshold ellipses as Δa*b*: (a) Ellipses of the present experiment; (b) Ellipses of Lv et al.'s experiment.*

At high spatial frequency, ellipse orientation 'θ' had h_{ab} of about 120°, which indicates that the contrast between chromaticity along 120° or 300° hue angle had the most difficult to distinguish, or the least strict tolerance. In the vertical direction, 30° or 210° axis, the contrast is the easiest to distinguish, or the smallest tolerance. Both sets showed that 'A/B' value increases (ellipse becomes longer) at high spatial frequency. This implies that the uniformity is unsatisfying at high spatial frequency.

At the later stage, another study was carried out to study a green color center, having coordinates in u'v' of 0.1449 and 0.4758 respectively. The conditions were set at spatial frequencies of 0.06, 0.12, 0.24, 0.48, 0.96, 1.92 and 3.84 cpd, and again along color directions of 0, 40, 70, 100, 120 and 150 degrees with u' axis. The experimental method was the same as that of the white center. The visual results for the green center were fitted to ellipses in a*b* plane. Figure 8 shows both the ellipses for the green and the white centers. Table 3 shows the ellipse parameters for the green center. It can be seen that A value of green center decreases from 0.06 to 0.24

cpd but increases after 0.24 cpd, which agrees with those found in the white center.

Table 2. Parameters of chromatic contrast threshold ellipses in a*b* plane

The present experiment				Lv *et al.*'s experiment			
SF(cpd)	A	A/B	θ(°)	SF(cpd)	A	A/B	θ(°)
0.06	1.74	3.43	121.21	0.5	1.04	2.17	118.11
0.12	0.71	1.97	140.10	1.0	1.34	2.61	110.04
0.24	0.60	2.07	135.55	2.6	3.55	4.16	117.43
0.48	1.02	2.19	121.51	5.2	5.52	3.45	128.33
0.96	1.41	2.74	121.76	7.8	13.26	5.54	121.30
1.92	3.02	2.90	124.06	11.7	17.56	4.73	118.33
3.84	4.78	3.34	123.16				

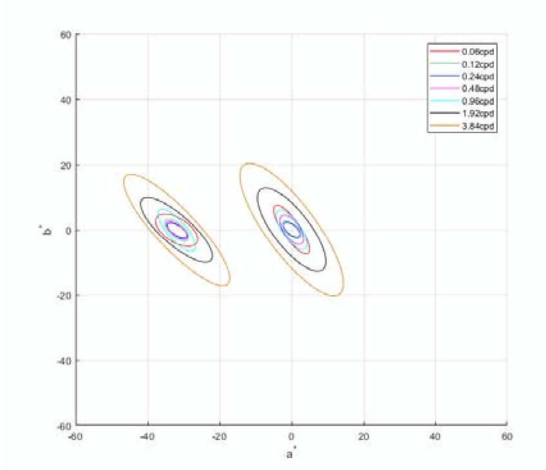


Figure 8. *Visible chromatic contrast threshold ellipses of green center and white center as Δa*b*.*

Table 3. Parameters of chromatic contrast threshold ellipses in a*b* plane

White Center				Green Center			
SF(cpd)	A	A/B	θ(°)	SF(cpd)	A	A/B	θ(°)
0.06	1.74	3.43	121.21	0.06	1.39	1.94	145.52
0.12	0.71	1.97	140.10	0.12	0.87	2.19	138.48
0.24	0.60	2.07	135.55	0.24	0.70	2.42	146.27
0.48	1.02	2.19	121.51	0.48	0.80	2.55	137.97
0.96	1.41	2.74	121.76	0.96	1.48	2.79	136.66
1.92	3.02	2.90	124.06	1.92	2.76	3.20	136.32
3.84	4.78	3.34	123.16	3.84	4.40	3.82	130.64

Chromatic contrast sensitivity functions (CCSF) of different color changing directions

Figures 9-11 show the JND of CCS in Δu'v' unit are expressed as a trend of spatial frequency in each color changing direction for the present white and green centers, and Vogel et al's white center, respectively.

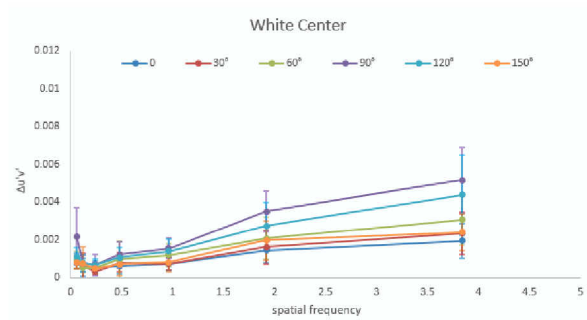


Figure 9. *Visible chromatic contrast thresholds as Δu'v' expressed as a trend of spatial frequency for each color changing direction of the white center in the present experiment.*

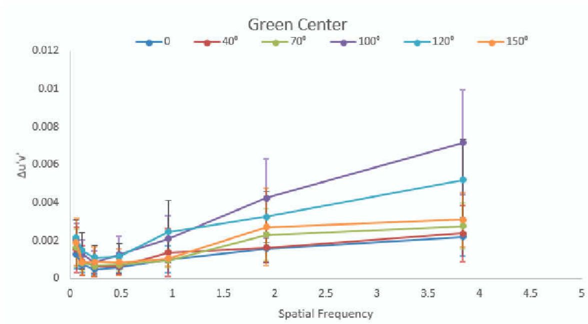


Figure 10. *Visible chromatic contrast thresholds as Δu'v' expressed as a trend of spatial frequency for each color changing direction of the green center in the present experiment.*

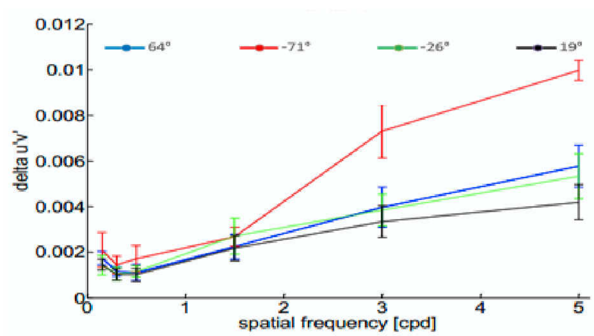


Figure 11. *Visible chromatic contrast thresholds as Δu'v' expressed as a trend of spatial frequency for each color changing direction in the experiment of Vogels et al.*

Figures 9-11 show that human visible CCS threshold decreases from 0.06 cpd to 0.24 cpd but increases after 0.24 cpd, which confirms the results found by Vogels *et al.* [1]. For 90° of white center, the thresholds were at their largest. And the second largest was at 120°. When spatial frequency is greater than 0.48 cpd, the threshold size for each spatial frequency is stabilized and becomes invariable. However, for the smaller spatial frequency, the order is varied. Comparing the results found by Vogels *et al*,in Figure 11, Figure 9 and Figure 10 had almost the same trend but their threshold sizes could vary, due to different color centers. In addition, 20 observers took part in the present experiment which is far more than those used in the other experiments.

In the previous investigations, CCS functions were fitted as low-pass curves. This experiment obtained similar results as previous at spatial frequency greater than 0.48 cpd. Nevertheless, CCSF cannot be fitted in the previous investigations because chromatic contrast sensitivity performs differently at low spatial frequency. It can be argued that at those low spatial frequencies the visual system cannot perceive the "frequency" and only judges parts of the pattern for the local contrast. In this work, we take the practical standpoint of defining everything using frequency, but do not claim that the results show directly a lower sensitivity of the visual system to lower frequency chromatic contrast patterns. As a clear effect on the number of visible periods of a periodic pattern on its visibility has been clearly demonstrated, the results we see could be explained by the inability of the visual system to perceive all the periods of the pattern that were presented. As this was not one of the goals of the study, we hope that future research will give more insights into the appropriate model to explain the effect.

Conclusion

An experiment was conducted to study the perceptibility of CCS threshold of different color changing directions and spatial frequencies for a white and a green color center. The results were used to fit visible CCS threshold ellipses and functions. It was found that the minimum threshold was also found the spatial frequency at 0.24 cpd. This indicates that chromatic contrast sensitivity reaches the peak at about 0.24 cpd. The results confirmed with the previous finding and can provide a theoretical basis for a model to be used in the lighting and imaging industries.

References

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

[2] 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.

[3] H. Yu, T. Jiang, C. Wang. Chromatic contrast sensitivity measurement based on the characteristics of display equipment. Chinese Journal of Liquid Crystals and Displays, 2016, 31(07): 655-660.

[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] 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.

[7] J. Shi. Color difference sensitivity of human vision system for red-green and yellow-blue directions. Proceedings of SPIE - The International Society for Optical Engineering, 2006, 6033:167-172.

[8] Y. Liu, J. Yang, Y. Lin, H. Lv. Research on medical applications of contrast sensitivity function to red–green gratings in 3D space. Neurocomputing, 2016.

[9] K. L Gunther, K. R. Dobkins. Individual differences in chromatic (red/green) contrast sensitivity are constrained by the relative number of L- versus M-cones in the eye. Vision Research, 2002, 42(11).

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

[18] M. Lucassen, M. Lambooij, D. Sekulovski, I. Vogels. Spatio-chromatic sensitivity explained by post-receptoral contrast. Journal of Vision 2018;18(5):13.

Author Biography

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