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Jianyong Zhang, Weiqi Jin, Weijie Hu, Xia Wang, "Theoretical study of chromatic contrast sensitivity function (CCSF)," Proc. SPIE 4922, Color Science and Imaging Technologies, (13 September 2002); doi: 10.1117/12.483117

SPIE.

Event: Photonics Asia, 2002, Shanghai, China

Theoretical study of chromatic Contrast Sensitivity function (CCSF)*

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There are lots of experimental results concerned with chromatic contrast detection (based on changes in chromatic distribution over space or time), but compared with luminance contrast detection, there has been no theory to describe chromatic contrast detection and thus no mathematic model for isoluminant contrast sensitivity function. After reviewing of many papers, two reasons may contribute to this: 1. Isoluminant contrast sensitivity function has the same description method as the isochromatic contrast sensitivity function which is unfit to express the chromatic changes. 2. The color vision is so complicated that further study is needed. Based on detailed analysis of previous works, this paper utilizes colorimetry fundamental principle to present a new theory for color contrast detection, and indicates that isoluminant contrast sensitivity function can be described by two aspects of chromatic changes——dominant wavelength and colorimetric purity. This theory can well explain that red-green and yellow-blue contrast sensitivity functions have similar characteristics.

Keywords:color contrast sensitivity, isoluminant , colorimetry, modulation transfer function

1 Introduction

The modulation transfer function (MTF) of human visual system has been widely applied to the evaluation of electro-optical imaging system. With the development of imaging technology and image fusion technology, the image for human eye has become color images from monochromatic images while traditional evaluation methods which utilize isochromatic MTF can't be applied in the evaluation. Therefore chromatic modulation transfer function (CMTF) is important to evaluation of color image.

Compared with luminance contrast detection, there has been no theory to describe chromatic contrast detection and thus no mathematic model for isoluminant contrast sensitivity function. Two reasons may contribute to this: 1. Isoluminant contrast sensitivity function has the same description method as the isochromatic contrast sensitivity function which is unfit to express the chromatic changes. 2. The color vision is so complicated that further study is needed. Based on detailed analysis of previous works, this paper utilizes colorimetry fundamental principle to present a new theory for color contrast detection, and indicates that isoluminant contrast sensitivity function can be described by two aspects of chromatic changes——dominant wavelength and colorimetric purity.

2 Chromatic contrast sensitivity function(CCSF)

* supported by fundamental research project of national defense fundamental research plan

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2.1 Luminance contrast detection

The study of luminance contrast detection in the human visual system has been dominated for the last 20 years by the methods derived from the concepts of linear systems analysis. Of course, the visual system has important nonlinearities. Nonetheless, there have been several successful applications of linear systems analysis in human vision.

A spatial sinusoid $I(x,y)$ can be described by:

$$I(x,y) = A\sin(2\pi fx + \phi) + \bar{I}$$

The contrast of a spatial sine wave is defined as $C = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, thus $C = A/\bar{I}$. When the contrast C of a sinusoidal grating (at a particular frequency) is increased from zero (while holding $\bar{I}$ fixed), there is a contrast at which it first becomes reliably detectable, and this value defines the contrast detection threshold. A plot of the reciprocal of contrast at threshold as a function of spatial frequency constitutes the contrast sensitivity function (CSF).

2.2 Human color spatial vision

Compared to the CSF, there is also a large literature concerned with chromatic contrast detection. That is to say, contrast detection based upon changes in chromatic distribution over space or time. Theoretically a chromatic spatial CSF is obtained by measuring thresholds for the detection of sine wave gratings that modulate spatially in color without modulating in luminance [1]. This is typically accomplished by adding two sine wave gratings of different wavelength distributions but the same luminance amplitude. The two gratings are added in opposite spatial phase so that the mean luminance is constant across the pattern; such a pattern is said to be isoluminant, for example as shown in fig 1. Formally, an isoluminant sine wave grating $I(x, y)$ can be defined as follows:

$$I(x, y) = \left(A\sin(2\pi fx) + \overline{I_1}\right) + \left(-A\sin(2\pi fx) + \overline{I_2}\right) \quad (1)$$

Where the first term on the right represents the grating for one of the wavelength distributions, and the second term on the right for the other distribution. The terms $\overline{I_1}$ and $\overline{I_2}$ are equal in units of luminance. Contrast sensitivity at spatial frequency f is measured by varying the common amplitude, A..

2.3 The review of the chromatic contrast sensitivity (CCSF) study

The mutually exclusive opponent colors, first described by Hering [Hering, 1878], are thought to reflect the representation of color in the central visual system that is composed of black-white, red-green and yellow-blue. The recent works [2], developed the Hering theory, consider that the human color vision can be divided to be several stages as shown in fig 2. At the first stage , three cone types which are long(L), middle(M), and short(S) human cone photopigments absorb different spectrum radiation and then at the second stage the stimulus is recoded into three opponent color signals ——black-white , red-green and yellow-blue. Based on the opponent-color theory, the chromatic contrast sensitivity (CCSF) study typically choose the red-green and yellow-blue isoluminant grating to measure contrast sensitivity of different opponent.

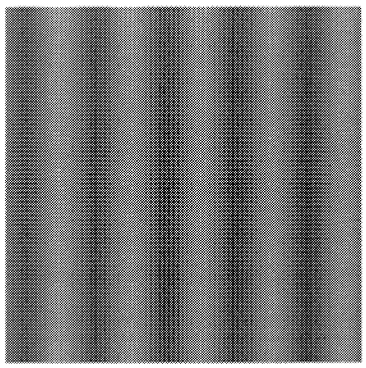


fig 1 Isoluminant grating

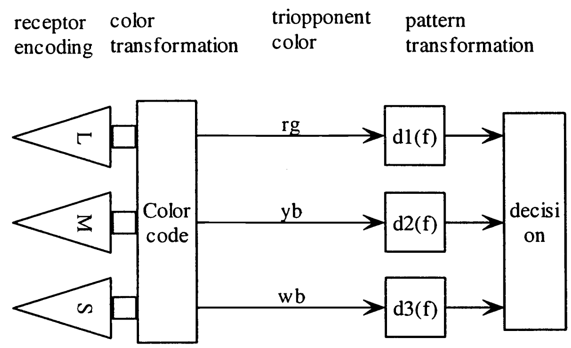


fig 2 Opponent color theory

The first study of the chromatic contrast sensitivity (CCSF) is Schade [3]. And then Van der Horst & Bouma [4] , Granger & Heurtley [5] and Kelly [6] have similar study and obtained the similar results. In the early studies most of them measure red-green gratings and only a few study measure yellow-blue gratings [4]. Furthermore these early studies have not extended to very low spatial frequencies, thus the results are not suitable to compare with the luminance contrast sensitivity. In recent studies, K. T. Mullen [7] detailed measure the red-green and yellow-blue gratings. Based on asymmetric matching and mass experiments, A. B. Poirson & B. A. Wandell [8,9] established the patten color separable model as shown in fig 3.

In above experiments, the luminance contrast of the mixed gratings $I(x, y)$ is used to express the color variation. The chromatic contrast is defined as follow [1]:

$$C = 2A/\left(\overline{I_1} + \overline{I_2}\right) \tag{2}$$

Though C is related to the color variation of the gratings over space, it can not precisely represent the color variation of the gratings and it seems more reasonable when the color variation over space is decomposed into three opponent in the study of A . B. Poirson & B. A. Wandell [8]. Because the opponent-color model don't have an international standard and there is great difference of opponent model between the experimental data, it is not convenient while comparing the result between different experiment. Based on detailed analysis of K. T. Mullen works [7], this paper utilizes colorimetry fundamental principle to present a new theory for color contrast detection, and indicates that isoluminant contrast sensitivity function can be described by two aspects of chromatic changes——dominant wavelength and colorimetric purity.

2.4 Chromatic contrast sensitivity based colorimetry

In the Kathy T. Mullen work [7], the 526nm and 602nm red-green pairs were chosen at the peaks of both the human opponent color spectral sensitivity function so that the red-green pairs is more independent of 577nm and 470nm yellow-blue pairs and vice versa. The mean luminance of the two composite gratings is constant and contrast of either component grating in each mixed grating is constant, thus $C_{526} = C_{602}$ and $C_{470} = C_{577}$ at all luminance. To find threshold, contrast is varied and at threshold the reciprocal contrast of either grating may taken as the contrast sensitivity.

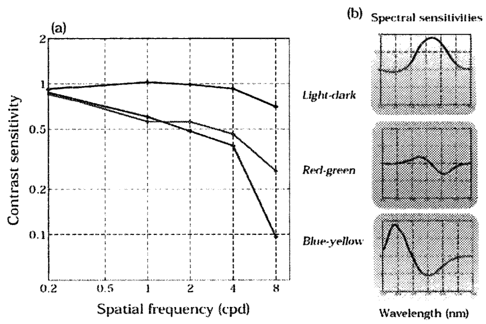


fig 3 pattern color separable model

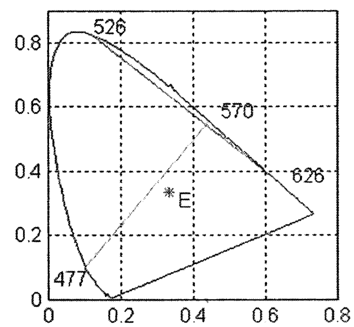


fig 4 the chromaticity coordinates of the mixed gratings

In the experiment, the ratio of the mean luminances of the two component gratings in the stimulus was varied over a wide range, and the subject's contrast sensitivity to the stimulus was measured at selected points. The criterion for the choice of the intensity mach was the luminance ratio at which the contrast sensitivity to the chromatic grating differs most from the contrast sensitivity to the monochromatic gratings.

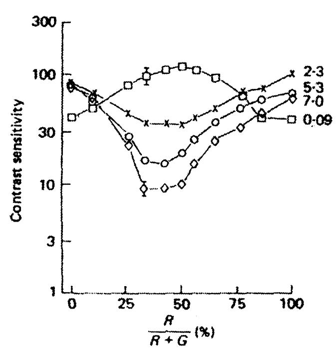


fig 5 Contrast sensitivity as a function of the red-green ratio in the stimulus

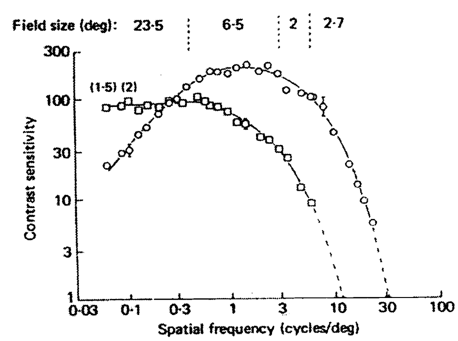


fig 6 contrast sensitivity as a function of spatial frequency for the red-green grating

The method is illustrated for the red-green in fig 5. The range begins and ends with a red or green monochromatic stimulus that has luminance contrast but no color contrast, and in the middle region the stimulus will have maximum color contrast and minimal luminance contrast over space. Then the contrast sensitivity function is obtained from intensity ratios at the maxima and minima as shown in fig 6. In conclusion K. T. Mullen gives that the contrast sensitivity of red-green is similar to the contrast sensitivity of yellow-blue and both are low-pass while the luminance contras are band-pass.

In the K. T. Mullen experiment the chromaticity coordinates are shown in fig 4 and E is the equal-energy stimulus. The chromaticity coordinate of the red-green composite grating is along the line which begins with 526nm monochromatic stimulus and ends with 602nm monochromatic stimulus, and the chromaticity coordinate of the yellow-blue composite grating is along the line which begins with 477nm monochromatic stimulus and ends with 570nm monochromatic stimulus For the isoluminant composite grating the only variety is the color changes over space to cause the contrast sensitivity change. If the color variety can be represented in appropriate colorimetry form, it can favor the investigation of chromatic contrast sensitivity and comparition between different results. The dominant wavelength of a color stimulus correlates in an approximate way with what would be called in ordinary language the hue of the color stimulus as observed under everyday conditions, while excitation purity correlates loosely with saturation of the color perceived under ordinary observing conditions. Thus for the color variety may be expressed by luminance, dominant wavelength and excitation purity.

Then the dominant wavelength change and excitation purity change of red-green composite grating in the stimulus is plotted in fig 7 and fig 8. As shown in the figure 8, the red-green composite grating is close to monochromatic grating because excitation purity is near to 0. As shown in the figure 7, the dominant wavelength change of the composite grating increases with the the percentage of red in the mixture and reaches maximum at 50% red, then decreases with the percentage of red. Compared to fig 5, the contrast sensitivity change corresponds to the dominant wavelength change. Then the stimulus in red-green grating can be expressed in dominant wavelength change that correlates in an approximate way with the hue of the color stimulus while separate from the excitation purity change. But as shown in fig 9 the mean luminance change of composite grating is not equal to 0 except 50% red so that the experiment didn't isolate the mean luminance change.

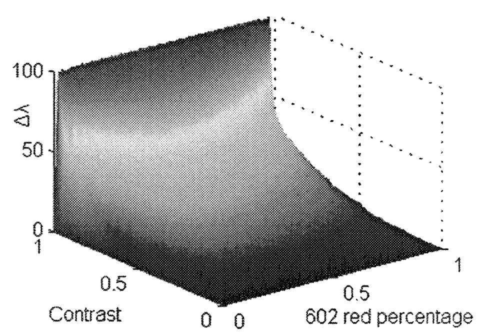


fig 7 the dominant wavelength change of composite grating

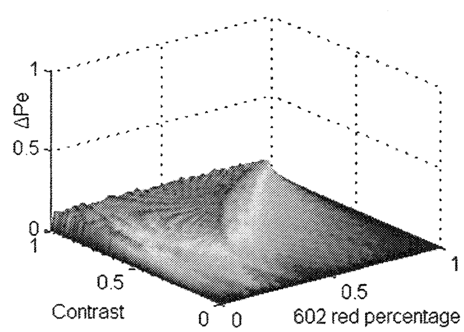


fig 8 the excitation purity change of the composite grating

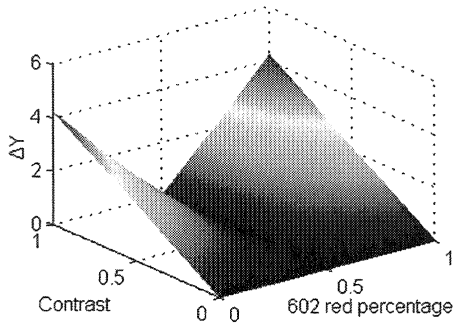


fig 9 the mean luminance change of the composite grating

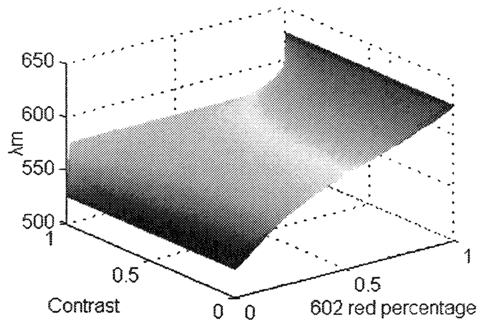


fig 10 the mean dominant wavelength of the composite grating

The dominant wavelength change and excitation purity change of yellow-blue composite grating in the stimulus is ploted in red- fig 11 and fig 12. As shown in the fig 11 and fig 14 , dominant wavelength change of the yellow-blue composite grating is near to 0 when the contrast is below 0.5. When contrast of the composite grating is below 0.5 and the percentage of yellow is below 0.5, the only obvious change is excitation purity. The excitation purity change of the composite grating increases with the the percentage of yellow in the mixture and reaches maximum above 50% yellow, then decreases with the percentage of yellow. Compared to K. T. Mullen experiment [7], the contrast sensitivity change corresponds to the excitation purity change. Then the stimulus in yellow-blue grating can be expressed in excitation purity change that loosely correlates with the saturation of the color stimulus while separate from the dominant wavelength change. But as shown in fig 13 the mean luminance change of composite grating is not equal to 0 except 50% yellow so that the experiment didn't isolate the mean luminance change.

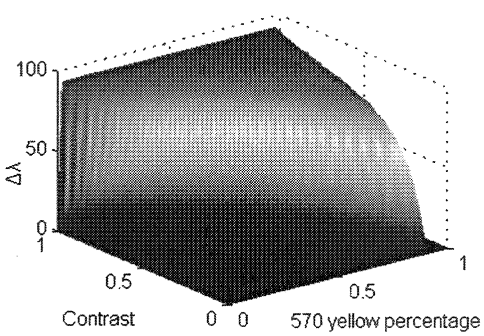


fig 11 the dominant wavelength change of composite grating

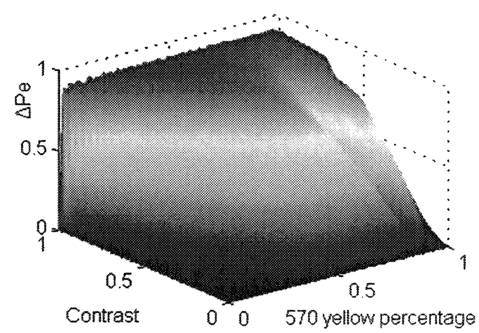
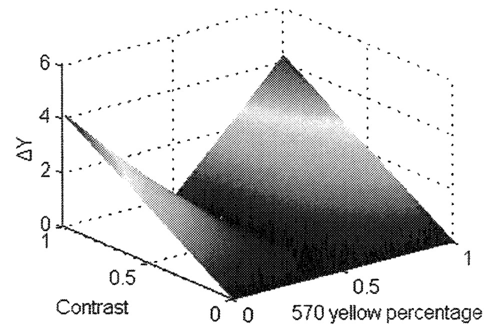


fig 12 the excitation purity change of the composite grating



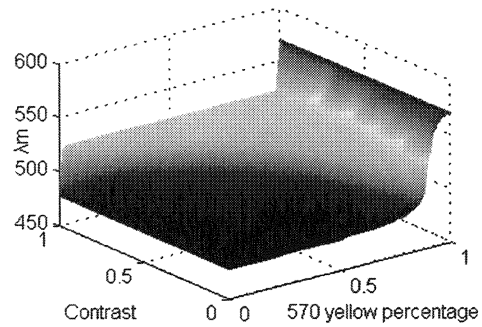
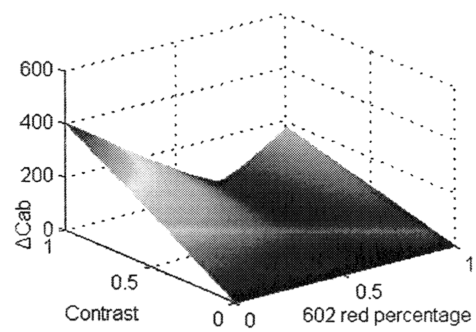


fig 13 the mean luminance change
of the composite grating

fig 14 the mean dominant wavelength
of the composite grating

Similarly the color variety of the composite grating can also be represented by the hue and chroma in $L^*a^*b^*$ color space as shown in fig 15, 16, 17, 18.



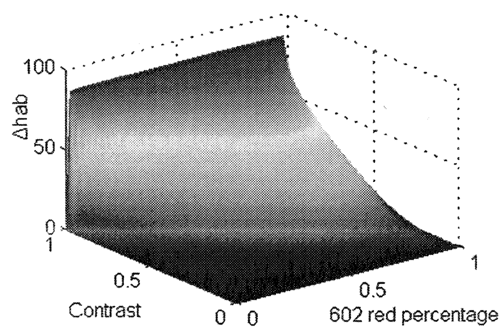
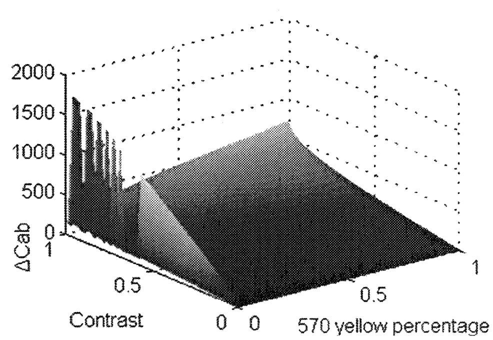


fig 15 the chroma change
of the red-green grating

fig 16 the hue change of the red-green composite grating



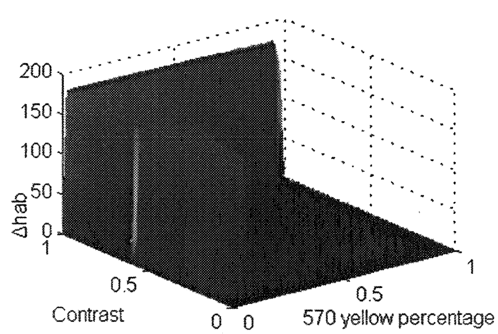


fig 17 the chroma change
of the yellow-blue grating

fig 18 the hue change of the yellow-blue composite grating

As shown in fig15 and fig 16 the red-green grating has both chroma and hue change yet the yellow-blue grating don't have chroma and hue change.

3 Conclusion

From the discussion above the human color spatial vision can be represented by dominant wavelength and excitation purity which agree with the experimental results. The dominant wavelength and excitation purity reveal two side of the human color spatial vision that dominant wavelength correlates in an approximate way with the hue change over space and excitation purity loosely correlates with saturation over space. Thus different experiments can be compared with each other in the same form and the concept chaos is avoided.

As indicated above the red-green pairs is more independent of yellow-blue pairs and vice versa, therefore the chroma change or hue change in $L^*a^*b^*$ color space should be only change of the red-green grating or yellow-blue grating and vice versa, but as shown above it is not true. So chroma change or hue change in $L^*a^*b^*$ color space is not chosen to represent the human color spatial vision.

According with the experiment of A. B. Poirson & B. A. Wandell [8,9] and their pattern color separable model, the coding of color is independent with the spatial function, thus we guess that the representation of color, by dominant wavelength and excitation purity , is independent with the spatial function.

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