A Measurement of the Lightness Contrast Sensitivity under Perceptual Color Space

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***Abstract* — To obtain the spatial frequency response of human vision under difference lightness, the paper measured the lightness contrast sensitivity by psychophysical experiment. The five color stimuli were selected in perceptual color space CIELAB. A series of sinusoidal grating images were made by Fourier analysis. Those images were displayed randomly on a calibrated color display system. Psychophysical experiments were carried out to obtain data sets of five lightness contrast sensitivity. Five contrast sensitivity function (CSF) curves have been fitted. The results showed that those CSF curves are different under different lightness. The peaks of the CSF curves are different. The experiment confirmed approximately the spatial frequency range of their peak is between 0.5~7cpd. The tendency of CSF is mainly manifested band-pass characteristics under the moderate lightness and the highly lightness, but shows low-pass characteristic under low lightness.**

Keywords - Human Color Vision; Contrast Sensitivity; Spatial Frequency; CIELAB

I. INTRODUCTION

The research of human visual spatial frequency response can be traced back to the fifties of 20th century. Some scientists have measured the response of human visual luminance contrast sensitivity by using different experiment methods[1,2,3,4,5,6,7,8,9,10,11], and some of them have built contrast sensitivity function (CSF), such as Barten model[4], S.daly model[5], Mannos and Sakrison model[6] and so on. Recently, some scholars made some relevant study based on the previous studies, and achieved valuable research production [7,8,9,10,11]. Those researchers employed different methods according to different objectives in the measurement of visual CSF. The early studies mainly adopted optical devices to produce stripes of different luminance contrast. This system was hard to design and control. With the widespread use of displays in recent years, many scholars use displays to do tests. In order to study image compression, Nadenau[10] using CRT display measured CSF in three different color space, such as CIELAB, YCbCr and LMS. Yang J. et al. measured CSF in CIELCH color space [11]. Looking at these reported experiments it is found that significantly more measurements were done for luminance CSF. The few existing measurements for color CSF are sometimes limited under middle lightness. Luminance is not the characteristic of human color vision. It is biophysical measurement. The color attribute of human vision include lightness, hue and saturation. So the lightness CSF represents the spatial frequency response of human vision. There is no measurement which aims at different lightness contrast sensitivity under perceptual color space. So it is necessary to measure once more the human CSF. The measurement of different lightness CSF has a great theoretical significance in guiding modern image processing technology based on standard color space.

II. MEASUREMENT METHODS FOR THE LIGHTNESS CONTRAST SENSITIVITY

A. Visual Stimulus

The CSF specifies the sensitivity of the HVS for a contrast at a specific frequency. The measurement of CSF is threshold experiments, to operate at the limit of the human ability to detect a pattern. The goal of experiment is to quantify this detection limit as function of the spatial frequency. The visual stimuli are usually circle-shaped sinusoidal patterns with a horizontally oriented grating. In this paper, the lightness test scope was expanded, the five different points in lightness axes of perceptual color space CIELAB were selected as the visual color stimulation. The five lightness values is L=10, L=25, L=50, L=75, L=90 , that represent those gray images in low dark, dark, middle, light and high light tone respectively. Using each lightness value (also called as center of lightness) as mean lightness of the visual stimulus makes image orders in which contrast changing based on different frequency of sine-wave. According to the step of spatial frequency to set a number of image sequences, which contains some different contrast images with black and white vertical stripe. The image orders include from image completely without the stripe to image with clear stripes. The computation of the image color data as showed in Equation (1):

$$I(x,y) = L(x,y) + \Delta L \times \sin 2\pi f x \quad (1)$$

Where, $I(x,y)$ is the lightness data of image, $L(x,y)$ means the center of lightness, f represents the variable of spatial frequency, ΔL shows the lightness aberration. During the generation process of image sequence, the range of f is [0-20] cpd and step is 0.98. The range of ΔL is [0, 1] and step is 0.001. The contrast of visual stimulus C is showed in Equation (2):

$$C = \frac{\Delta L}{L(x, y)} \quad (2)$$

Equation (2) is the basic contrast definitions of the Michelson and Weber-contrast. The max lightness of the image is $I(x, y) + \Delta L$. The min lightness of the image is $I(x, y) - \Delta L$. One of the visual stimuli of the 5 lightness is showed Fig. (1).

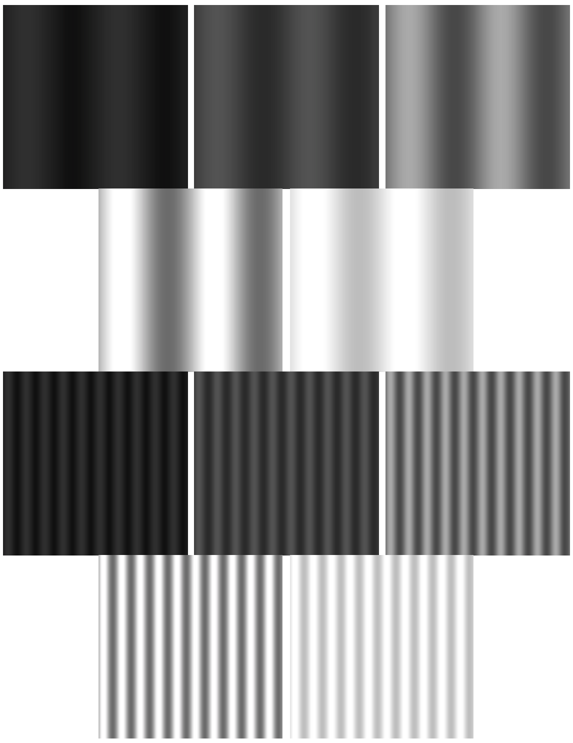

Fig.1 An Example of The 5 Lightness Visual Stimuli

B. Testing Procedure

For threshold detection experiments special display devices are necessary that allow a very fine color quantization. Display as the common device is used for image displaying and processing. This experiment used NEC PA272W 27” LCD display, and the measure conditions of contrast sensitivity was based on the regulation of Spatial Standard Observer(SSO) of ModelFest organization founded by the Optical Society of America(OSA) to set the experimental parameters, which was showed in Table I. The display system should be color calibrated using corresponding software SpectraView and Xrite-i1 Pro2 to generate display ICC profile. The results of calibration are: the luminance level of display is 119 cd/m2 (the setting target is 120 cd/m2); Color temperature is 6515K (the setting target is D65); Contrast is 698 : 1 (the setting target is 1000 : 1); Gama is 2.2 (the setting target is 2.2); The maximum value of the color different of lightness ⊿E94 is 1.8 and mean value 0.66. In order to keep the consistence of color display, the device should be preheated at least half an hour before every experiment and be calibrated regularly.

TABLE. I CONDİTİONS AND REQUİREMENTS OF THE EXPERİMENT

Item	Parameter	Item	Parameter
Brightness	≥30±5 cd/m2	Contrast	1000：1
Refresh frequency	60Hz	Gamut	99.3% Adobe RGB
Stimulus size	512 × 512 Pixels	Gama	1.0-2.6
Pixel size	0.233	Visual angle	178°
Viewing distance	1.6m	Color temperature	3000-15000K
Requirements	Eyesight	Resolution	2540×1440

Beside the test patterns, also the testing method has to be defined. That means how the patterns are represented and how the observer’s response is treated. The viewing condition is in a dark environment, which means the only light was from the experimental display. Six observers with normal vision were selected, who have vision or corrected vision over 1.0 and aged around 19-22 years old. Before the experiment, every observer should adapt to the dark environment at least 5 minutes. Each experiment time will not over 40 minutes and the observer should wear gray clothes when doing the test. The stimulus image sequences of every lightness center were made by the method of fixed spatial frequency based on contrast changing. Every time one observer will finish one test of an image sequence. The test images will be showed randomly on the display and observers will face up to the stimulus images. When finding any with just noticeable contrast difference of stripes, they can give a vote to this image by click the mouse, which will be recorded by the test system automatically with the spatial frequency value and contrast value of this image. All the experiment requires each observer to do twice.

III. TEST RESULTS AND ANALYSIS

A. Processing of Abnormal Data

The experiment has chosen 5 lightness centers and 11 spatial frequencies. Each image sequence includes at least 80 images, about 4.4×103 visual stimuli images have been made for this experiment. Each observer has to do the test twice, so there are 8.8×103 observations for each. The experiment has lasted 20 weeks to measure the five

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lightness contrast sensitivity. The test has showed a probability event that different observers have different contrast sensitivity to the same spatial frequency of the same color center. The measured data of the same lightness was made up of a 12×11 matrix, so called observed matrix.

The scatter of those measured values different lightness was showed Fig. (2). Where, the vertical axes is contrast sensitivity, the horizontal axes is spatial frequency. Fig2 produced a box plot of the data of the same frequency in the observed matrix. There is one box per column. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. As we can see in Fig. (2), there are some observed data have huge difference compared to others, which may cause by the abnormal factors of the system during the process of experiment. These data are belongs to abnormal data, which should be removed according to certain principle. Besides, the results showed that observer has high dispersion in low frequency area while centralized in high frequency area, which indicated that observers are more sensitive to low frequency are resulting the huge difference. If there are 0.001 contrast variation has been captured by observers, the contrast sensitivity is 1000, that is the main reason why observed data has high dispersion in low frequency area. While some data in high frequency area deviate largely from others, which may belongs to abnormal data. This may increase the experimental error or even lead to the distortion of experimental results if these abnormal data have been calculated in the computation of experiment results.

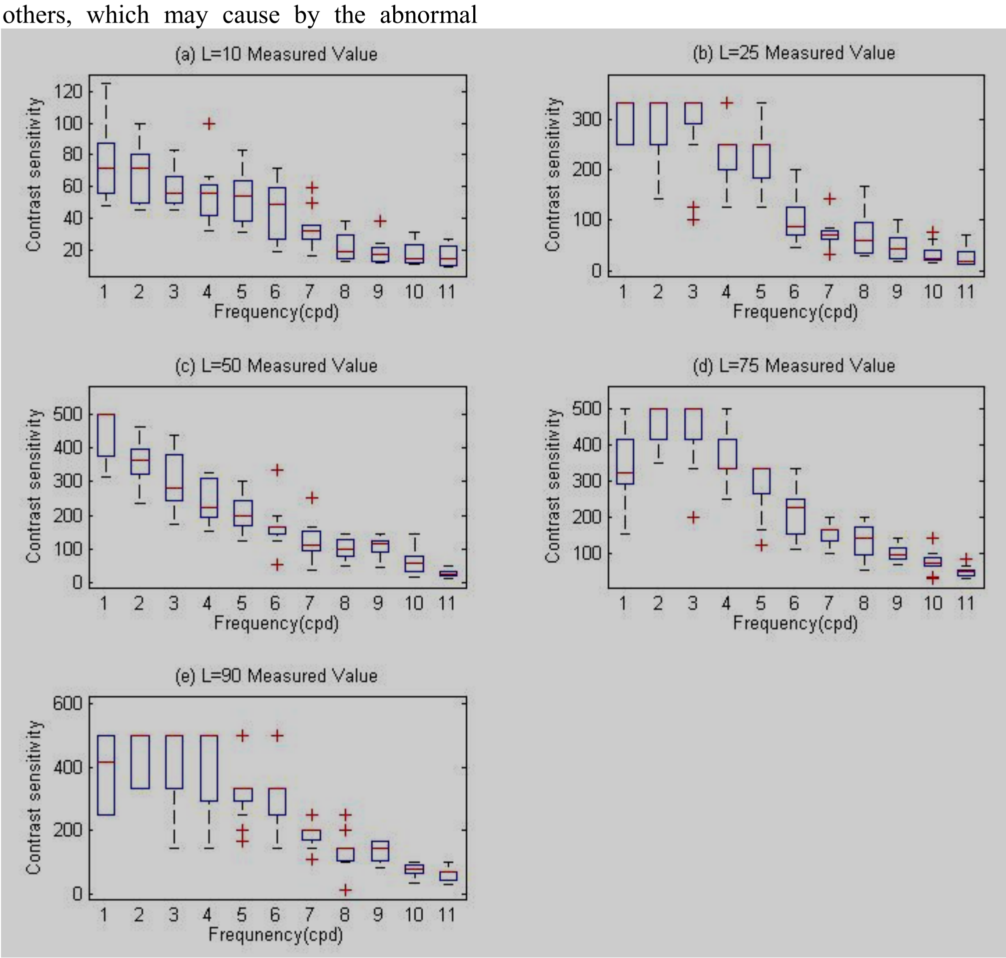

Fig.2 The Scatter box of The Measured data

However, it is not reasonable to remove high error data in order to get higher accuracy results, since those data may conform to random fluctuation with normal deviation of test values [12]. The processing of abnormal data usually has two methods: Chauvenet's Criterion and Grubbs Criterion. The choice between the two criteria can be determined by the number of measurements. For example, as for the number of measurement n<25, the coefficient of Grubbs Criterion $\lambda^{'}(\alpha,n)$ is sensitive to the changes of measurement, which makes it easy to remove test values with higher error [13]. The number of measurement in our experiments is 12, so Grubbs Criterion has been employed to process the abnormal data (confidence interval α is 0.01). The specific methods and principles are as following:

Set n measurement value in order of data size $x_1 \leq x_2 \leq \cdots \leq x_n$, and suppose x_n is the abnormal data needed to test and discriminate. S and Sn are the formula of test values, and the corresponding probability density is showed in Equation (3).

$$P = \left\{ \frac{x_n - \bar{x}}{s} < \lambda'(\alpha, n) = 1 - \alpha \right\} \tag{3}$$

so,

$$x_n - \bar{x} > \lambda'(\alpha, n) S = \lambda'(\alpha, n) \sqrt{\frac{n-1}{n}} \sigma = \lambda'(\alpha, n) \sigma \tag{4}$$

By looking up normal distribution table, we know that $\lambda'(\alpha, n)$, σ are the standard deviation of test data. Whether the abnormal data need to be removed or not according to the residual between abnormal data x_n and mean $\bar{x}$ is bigger than $\lambda'(\alpha, n)$ times sample standard deviation σ.

B. The computation of contrast sensitivity

In order to ensure the validity of data, the observed data has been processed by abnormal data method to remove those higher error data caused by system. The observed value of the image sequence in the same spatial frequency obtained from 6 observers represents the contrast sensitivity characteristics of individual. Different peoples have different results of contrast judgment in the different spatial frequency since they have their own human visual system. To show the commonality of the 6 observers, the mean observed data of them can represent the visual features of majority. The series of images in the experiment generate from varied contrast from small to large based on fixed spatial frequency. So the original data obtained from every observer is the pair of spatial frequency and contrast, and the contrast need to be transferred to contrast sensitivity. The method of computation is as following:

Suppose spatial frequency is $f_i(f_1 \cdots f_n)$, the contrast of 6 observers are $x_i(x_1 \cdots x_p)$, then the mean contrast sensation of them as in Equation (5):

$$\bar{x} = \sum_{i=1}^{p} x_i \tag{5}$$

The contrast sensitivity C can be calculated as in Equation (6):

$$C = \frac{1}{\bar{x}} \tag{6}$$

Therefore, the data pair of spatial frequency f_i $(f_1 .. f_n)$ and contrast sensitivity C_i $(C_1 ... C_n)$ has been generated.

C. Fitting to the CSF Model

The model assumes for the lightness CSF a sum of two Gauss functions to create a curve with band-pass characteristic (such as in [4,5,6] and [14]), which has been adopted as fitting mean observed value of basic function. The corresponding formulas are given in Equation (7):

$$S_L(f) = a_1 \exp(-(\frac{f - b_1}{c_1})^2) + a_2 \exp(-(\frac{f - b_2}{c_2})^2) \tag{7}$$

Where, S_L indicates the sensitivity for the lightness, the parameters a_1, a_2, b_1, b_2 and c_1, c_2 are subject to the parameter fit, f is the spatial frequency in cpd.

The raw-data fit is a least-mean square fit. Those coefficients of the 5 CSF curves are showed in Table II. Fig (3) shows the raw-data fit of the model.

TABLE II. RESULTİNG PARAMETERS FOR THE LİGHTNESS CSF MODEL

Parameter	a1	b1	c1	a2	b2	c2	R-square
L=10	70.79	0	14.53	0	0	0	0.98
L=25	304	1.89	9.72	0	0	0	0.969
L=50	385	0	11.89	0	0	0	0.94
L=75	333.9	3.36	4.77	178.7	8.90	9.73	0.997
L=90	422.6	3.25	11.23	0	0	0	0.9965

The parameters of R-square showed in Table II.represent the fitting degree between function and testing data. The finally resulting CSF curves are shown in Fig. (3), where the horizontal axes represent spatial frequency and vertical axes represents the contrast sensitivity. From bottom to top, Fig. (3) showed the curves of CSF_L10、CSF_L25、CSF_L50、CSF_L75 and CSF_L90. It can be observed that the curve vary in particular in their peak.

From comparison of the five CSF curves, we can find that: different lightness has different CSF. As for the curve of CSF_L10, it is lower, relative flat and has small cut-off frequency, which represents that human vision has weak contrast discrimination under lower lightness and can hardly distinguish the difference of adjacent area of image in high spatial frequency. With the lightness value increasing, the curves increased obvious, like they become more relative steep and the cut-off frequency increased also. The curves' peak of different lightness CSF is different, which means that human vision has different sensitive spatial frequency under different lightness center and the higher lightness value has the higher sensitive spatial frequency. If based on the relative position of the curves In Fig. (3) to compare, the curve of CSF_L75 compares to the curve of CSF_L90, the former curve is higher than the later one in the spatial frequency (2-6cpd), which means that human vision has highest contrast discrimination capability under L=75. In this case, we can tell that human vision has the highest contrast discrimination capability under medium above lightness and lower spatial frequency. As showed from the shape of curves, the tendency of CSF_L75 curve under L=75 is similar to the luminance CSF of other researches, which represents that human lightness vision has band-pass feature. However, the CSF data of the existing studies few measured under different lightness. The experiment measured CSF in five different lightness centers. The stimuli images were obtained in 4.1° field of view. It is more close to the common display size.

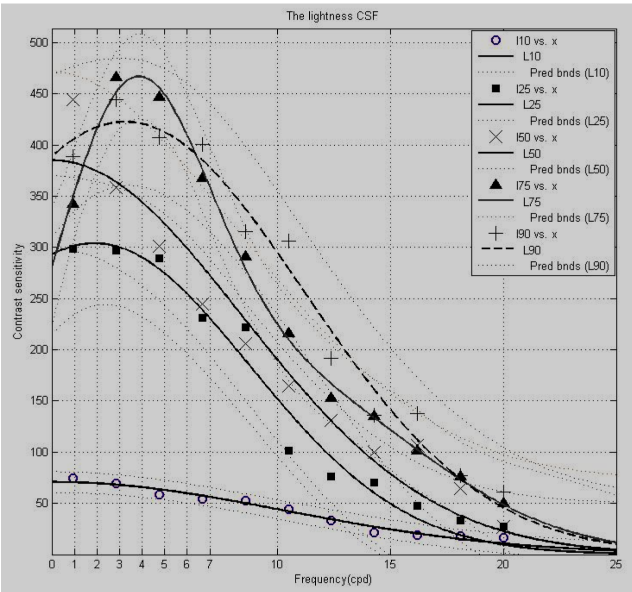

Fig.3 Curves of fitted raw data for the lightness of the CIELAB

IV. CONCLUSIONS

In this experiment, the field of view is 4.20 × 4.20, observation experiment was implemented in perceptual uniform color space CIELAB, data sets of contrast sensitivity of five lightness centers have been obtained and used to fit the CSF curves. Despite the different lightness center, CSF showed the same regularity: human vision is more sensitive to lower frequency than to higher frequency. However, the difference is that CSF curve of lower lightness is lower while that of higher lightness is relative higher. In the same spatial frequency, visual contrast sensitivity is higher when the lightness increasing. With the improvement of the lightness, the peak of CSF curves is moving to higher spatial frequency, confirmed from the experiment observed data, the spatial frequency range of the peak is around (0.5-7) cpd. Human vision is more sensitive to medium above lightness in low frequency, while in the high frequency is more sensitive to higher lightness. In the study of luminance contrast sensitivity, the CSF represents as band-pass feature. In our experiment the higher lightness CSF is band-pass feature. However, the lower lightness CSF has no obvious band-pass feature, is tending to low-pass feature.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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