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A Study of Spatial Chromatic Contrast Sensitivity Based on Different Colors, Luminance, and Stimulus Patterns

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Abstract

The goals of this work are to accumulate experimental data on contrast sensitivity functions and to establish a visual model that incorporates spatial frequency dependence. In the experimental design, two patterns were compared: fixed-size and fixed-cycle stimuli from different luminance levels. The detection thresholds have been measured for chromatic contrast patterns at different spatial frequencies. The present experiment was conducted with the aim to form a most comprehensive data by combining with our data. The experimental parameters including (1) five colour centres (white, red, yellow, green and blue), which were recommended by the International Commission on Illumination (CIE), at two different luminance levels for each colour centre; (2) three colour directions for each colour centre, namely luminance, red-green and yellow-blue and (3) five spatial frequencies, 0.06, 0.24, 0.96, 3.84 and 6.00 cycles per degree (cpd). The present and our earlier data were combined to form a complete set data to develop and test different models. A 10-bit display characterized by GOG model was used to obtain contrast thresholds of different color centers by the 2-alternative forced choice method and stair-case method. The experimental results revealed different parametric effects and also confirmed the McCann's finding that the number of cycles affects the comparative sensitivity. Finally, a cone contrast model and a postreceptoral contrast model proposed by Mantiuk et al was developed by fitting the visual test data (fixed number of cycles and fixed size). The models could accurately predict the contrast sensitivity of different color centers, spatial frequencies and stimulus.

Introduction

The human visual system is known to have different sensitivities for contrast patterns at different spatial frequencies. The function to describe this dependence for sinusoidal patterns is called the contrast sensitivity function (CSF). CSF is widely used in image processing and color difference evaluation, and also plays a key role in establishing the new illumination uniformity evaluation system including spatial frequency factors.

The CSF for luminance patterns has been studied extensively and has been robustly modeled. The chromatic CSF, compared with the luminance CSF, is affected by multiple factors such as color center and the direction of color modulation, thus hasn't been thoroughly studied and lacks a generic model. Since the 1950s, many visual psychophysical experiments have been carried out to investigate chromatic contrast sensitivity, usually using sine-wave patterns modulated in different color directions [1]–[8].

Chromatic contrast sensitivity was simplified and modelled as low-pass Gaussian functions about spatial frequency in the sCIELAB color-difference metric [9]. Equation (1) gives the contrast sensitivity:

$$S = \left(\frac{1}{\sqrt{3}}\sqrt{\left(\frac{\Delta L}{L_0}\right)^2 + \left(\frac{\Delta M}{M_0}\right)^2 + \left(\frac{\Delta S}{S_0}\right)^2}\right)^{-1}. \quad (1)$$

In 2021, Lucassen [10] et al. provided two models, known as the cone-contrast model (CCM) and the postreceptoral-contrast model (PCM). Both models were given in the form of look-up tables. The same year, Mantiuk [11] et al. conducted a comprehensive analysis of multiple databases and developed math Models of CCM and PCM with stronger versatility and adaptability.

In Mantiuk's cone contrast model, the visual increment response received by L, M, and S cone receptors can be encoded as cone contrast signals ($\frac{\Delta L}{L}$, $\frac{\Delta M}{M}$, $\frac{\Delta S}{S}$), which are combined to form mechanism responses corresponding to the three channels of opponent color space, known as ΔC_A (Achromatic), ΔC_R (Red-green), ΔC_B (Blue-yellow). The calculation matrix is as follows.

$$\begin{bmatrix}\Delta C_A\\ \Delta C_R\\ \Delta C_B\end{bmatrix} = \begin{bmatrix}1 & m_{1,2} & m_{1,3}\\ 1 & -m_{2,2} & m_{2,3}\\ -m_{3,1} & -m_{3,2} & 1\end{bmatrix} \cdot \begin{bmatrix}\Delta L/L_0\\ \Delta M/M_0\\ \Delta S/S_0\end{bmatrix}, \quad (2)$$

Mantiuk et al. model sensitivity function as a product of inverse log-parabola and a modified stimulus size term. The details are provided in the original paper [11].

The calculation process of PCM and CCM is similar, only the cone contrast in formula (2) needs to be replaced with the post-receptor contrast, see equations (3) and (4) for details:

$$\begin{bmatrix}\Delta C_A'\\ \Delta C_R'\\ \Delta C_B'\end{bmatrix} = \begin{bmatrix}1 & m_{1,2} & m_{1,3}\\ 1 & -m_{2,2} & m_{2,3}\\ -m_{3,1} & -m_{3,2} & 1\end{bmatrix} \cdot \begin{bmatrix}\Delta L\\ \Delta M\\ \Delta S\end{bmatrix} \quad (3)$$

$$\Delta C_A = \frac{\Delta C_A'}{Y},\ \Delta C_R = \frac{\Delta C_R'}{Y},\ \Delta C_B = \frac{\Delta C_B'}{Y} \quad (4)$$

The goal of the present research is to combine our earlier data [18] into a comprehensive data set by completing the lacking blue color center data for fixed-cycle and adding the measurement of fixed-size stimuli for all the 10 color centers, then developed at least one versatile model based on the data set. A threshold method based on forced-choice stair-case was adopted to assess just noticeable or threshold color difference of fixed-cycles and fixed-size stimuli in 3 color changing directions at 5 spatial frequencies. A cone-contrast model and a postreceptoral-contrast model was developed by fitting the data.

Experiment

Stimulus

The color backgrounds (color centers) were selected close to the 5 CIE centers recommended to study color difference [12], i.e., white (W), red (R), yellow (Y), green (G) and blue (B). For each color background, stimulus was set two different luminance levels, high (H) and low (L) levels. The color centers were represented as WH, WL, RH, RL, YH, YL, GH, GL, BH and BL respectively. Table 1 lists the chromaticity and luminance of the color centers, arranged in order of luminance from the highest to the lowest. The display peak white was set at either 300 or 100 cd/m^2 for the color centers brighter or darker than 50 cd/m^2, respectively. The color stimulus was modulated along three color directions for each color center, i.e., luminance (achromatic), red-green (R-G) and yellow-blue (Y-B). Five spatial frequencies, 0.06, 0.24, 0.96, 3.84 and 6.00 cycles per degree (cpd) were selected for both fixed-cycles (fc) and fixed-size (fs) stimulation.

Table 1: Chromaticity (in CIE) and luminance of the colour centres

	x	y	L (cd/m^2)
WH	0.314	0.331	216
WL	0.314	0.331	36
YH	0.219	0.216	150
YL	0.219	0.216	50
GH	0.248	0.362	72
GL	0.248	0.362	24
BH	0.388	0.428	26.4
BL	0.388	0.428	8.8
RH	0.484	0.342	14.1
RL	0.484	0.342	7.1

Each observer viewed the screen from a distance of 60 centimeters and the total field of view (FoV) was 60° × 34°. The chromaticity difference was multiplied with a Gaussian-shaped function (σ of 0.5/sf for fixed cycles, and 34°/4=8.5°for fixed-size) to eliminate the effect of the edges. The background chromaticity of the screen was the same as the color center of the sinusoidal pattern. The patterns were oriented either horizontally or vertically. It is assumed that both patterns would give the same threshold [13], [14].

Fig. 1 showed an example of the chromatic patterns. The left column shows the fixed-size stimuli, and the right column shows the fixed-cycle ones. The spatial frequency increases from top to bottom. In order to display the stripe pattern more clearly, the center of the picture is magnified and displayed in the upper right corner.

Monitor Characterization

The experiment was conducted in a dark room. Spatial contrast patterns were presented on a 10-bit 'NEC PA311D' LCD display with 2560 × 1440 pixels, which was set at a constant peak luminance of either 300 or 100 cd/m^2 and calibrated using a Gain-Offset-Gamma (GOG) model [15]. All the measurements were conducted using a Konica Minolta CS2000A tele-spectroradiometer. All results were reported for the CIE 1964 standard colorimetric observer. The display had a mean prediction accuracy of 0.43 ΔE_{00} (0.58 ΔE^*_{ab}) and 0.42 ΔE_{00} (0.61 ΔE^*_{ab}) from the color patches of 24 colors on an X-Rite Macbeth ColorChecker chart (MCCC) for 300 and 100 cd/m^2, respectively. The relatively small color differences reported for each parameter measured suggest that the display provides high quality, repeatable images and was suitable for the visual experiments.

The uniformity property was tested by measuring 9 equal portions (3 by 3) of the screen. Four colors were measured, i.e., white, red, green and blue. The mean color difference was 0.61 ΔE_{00}, which is relatively small.

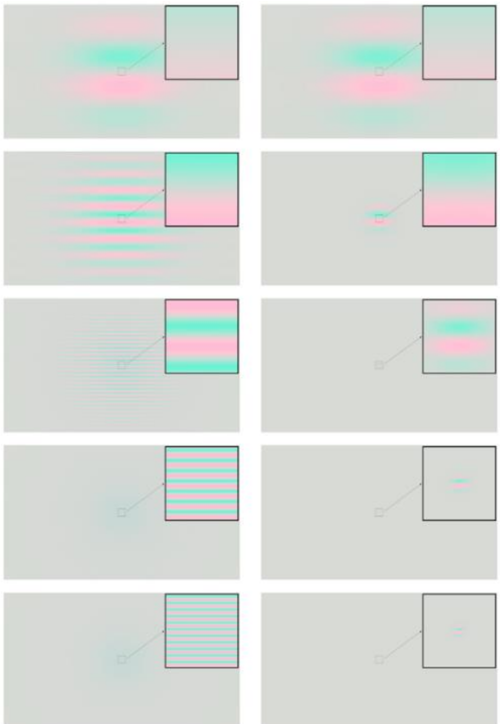

Figure 1. *Chromatic patterns for fixed-size and fixed-cycles stimuli.*

Observers

For each color center, 20 observers ranging in age from 20 to 30 years were involved. Each observer took part in the experiment of at least 2 color centers. All observers had tested visual acuity or corrected visual acuity of 1.0 and normal color vision according to the Ishihara color vision test.

Procedure

Each experimental session lasted about 2 hours for each observer and included two color centers. The process was divided into 6 sessions, with the first three session for the first color center and the last three for the second color center. Each session made 30 judgments and lasted about 20 minutes, with a 5-minute break between each session. The entire experiment took about 120 hours for all 20 observers.

Prior to the experiment, the Ishihara vision test was conducted. A written instruction was then given. Observers sat on a chair and used a chin rest to ensure the viewing distance of 60 centimeters resulting in the effective display resolution of 41 pixels per degree. A homogeneous image with the same luminance and chromaticity as the color center (background) was shown on the screen. Observers were asked to adapt the background color for one minute. 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 the completion of each stimulus, the adaptation image of the background color was again presented for 1 seconds to eliminate the after-image caused by the visual persistence. All the 15 conditions (5 spatial frequency × 3 color directions) and the direction of grating (horizontal or vertical) were arranged in a random order.

Visible color difference thresholds were determined using the three-up / one-down weighted stair-case method using a forced choice[16]. The stair-case procedure ended after nine reversal points, about 40 trials of the staircase. The detailed procedure can be found in an earlier publication. The thresholds were determined for the 75% of detection by fitting psychophysical function to the measurements [17].

Results

Inter-observer Variation

Inter-observer variation was the investigated by calculating the root-mean square error (RMSE, in dB units) of contrast sensitivity in logarithmic units (log10(S)) for each frequency at a given color center (background). Table 2 lists the inter-observer variation of both fixed-size (fs) and fixed-cycle (fc) stimuli.

Table 2: Inter-observer variation (RMSE, in dB units)

Color center	inter-observer variation	
	fs	fc
WH	4.8	4.0
WL	4.8	8.7
RH	6.5	5.5
RL	4.8	8.7
YH	5.1	4.7
YL	6.4	5.7
GH	7.6	4.8
GL	6.9	5.3
BH	6.3	4.9
BL	5.3	6.1
Mean	5.85	5.84
Total	5.8	

Contrast Sensitivity Results

Fig. 2 shows the contrast sensitivity results. From Fig. 2, the right row shows that for fixed-cycle stimuli, the achromatic channel shows band-pass behavior and the peak occurs at a spatial frequency between 0.24 and 0.96 cpd. Meanwhile, for fixed-size stimuli, the peak of the achromatic channel occurs around 0.96 cpd. For both fixed-cycle and fixed-size stimuli, the R-G and Y-B channels show low-pass trend, while for fixed-size stimuli, the R-G and Y-B color direcitons show slight band-pass trend between 0.06-0.96 cpd.

Fig. 3 shows the scatter plots of the logarithmic contrast sensitivity for the high and low luminance levels of each color center. The sensitivity data trend line is above the 45° straight line, and the slope of the trend lines of the three channels is 1.04, 1.03, and 1.04, respectively. Thus, the contrast sensitivities of the high luminance levels were slightly larger than those of the low luminance levels.

This verifies Mantiuk et al.'s [11] finding about contrast sensitivity for a large range of luminance levels, i.e., contrast sensitivity increases with luminance first and reaches the peak at about 200 cd/m^2, and then decreases (the brightest luminance of the color centers in the present experiment is 216 cd/m^2). In the above study, the change scale of luminance was 10 times (that is, adjacent brightness levels differ by 1 on a logarithmic scale of $\log_{10}$), while in this study, the luminance ratios used for white, yellow, green, red, and blue were 6 (216 cd/m²: 36 cd/m²), 3 (150 cd/m²: 50 cd/m²), 3 (72 cd/m²: 24 cd/m²), 2 (14.1 cd/m²: 7.1 cd/m²), and 3 (26.4 cd/m²: 8.1 cd/m²), respectively. The ratio of this study is smaller than that of Mantiuk et al.'s study, so the trend of contrast sensitivity with changes in luminance is not as obvious.

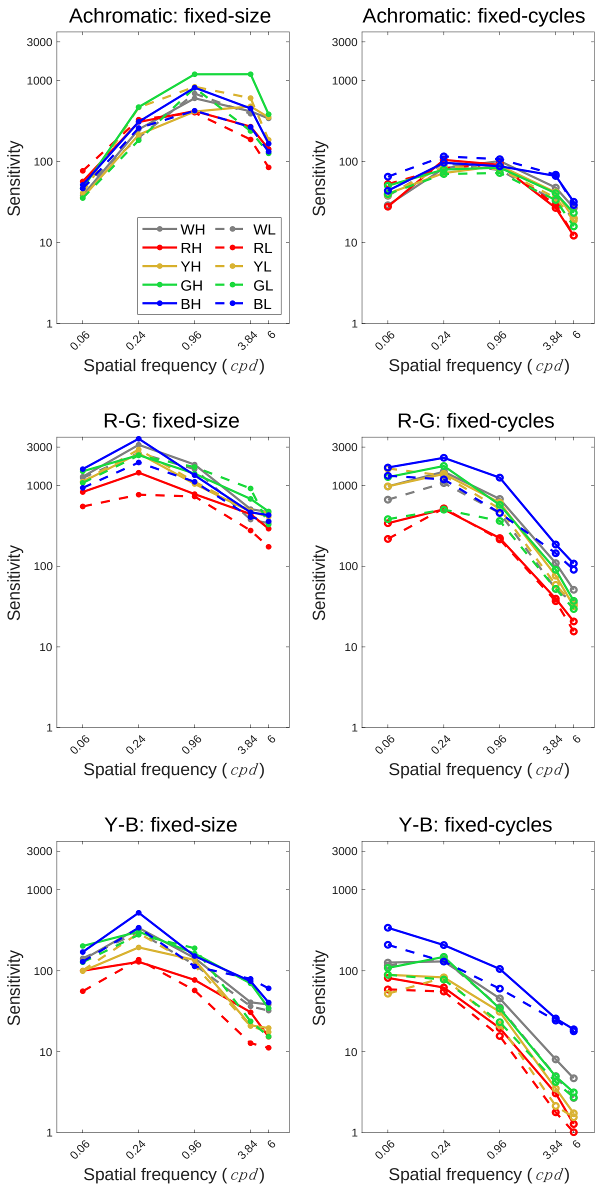

Figure 2. Contrast sensitivity results for fixed-cycles and fixed-size stimuli.

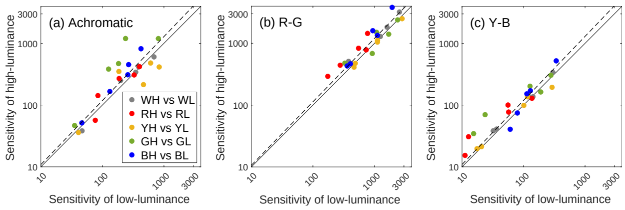

Figure 3. *Comparison of the logarithmic contrast sensitivity at high/low luminance. Note each centre's luminance values are different.*

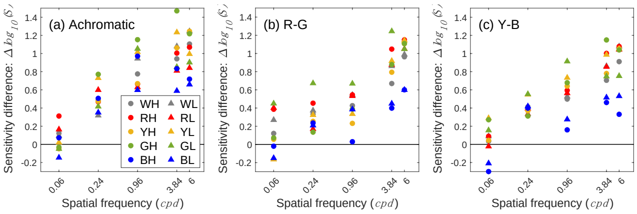

Figure 4. *Contrast sensitivity difference diagram of the fixed-size and fixed-cycle stimuli with spatial frequency change.*

Fig. 4 shows the scatter plots of the difference of the logarithmic contrast sensitivity ($\log_{10}$(S)) for fixed-cycles and fixed-size stimuli at the same spatial frequency. In general, with the increase of spatial frequency, the difference of sensitivities between two stimulus patterns also increases. In the present experiment, the fixed-cycles stimuli had two cycles of gratings, while the fixed-size stimuli contain 2, 8, 33, 131 and 204 periods at spatial frequencies of 0.06 to 6 cpd. For the majority of spatial frequencies (0.96 - 6 cpd), the contrast sensitivities of fixed-size stimuli are significantly higher than that of the fixed-cycle stimuli; at a spatial frequency of 0.24 cpd, the contrast sensitivities of fixed-size stimuli are only slightly higher than that of fixed-cycle stimuli. At the lowest spatial frequency (0.06 cpd), the difference of sensitivities between two stimulus patterns is around zero, indicating that the contrast sensitivity under fixed-size and fixed-cycle stimuli is similar.

Modelling Chromatic CSF

The contrast sensitivity data were used to fit Mantiuk *et al.*'s [11] cone-contrast model (CCM) and postreceptoral-contrast (PCM) model. The fitting error was reported as dB, calculated by multiplying the RMSE of contrast sensitivity in logarithmic unit (*log10(S)*) by 20. The loss function is given in equation (5):

$$L = 20 \times \sqrt{\frac{1}{N}\sum_{i=1}^{n}(log_{10}(\tilde{S}_i) - log_{10}(S_i))^2}. \qquad (5)$$

The contrast sensitivity prediction results of the fixed-size and fixed-cycle stimuli for 10 color centers using the optimized CCM are shown in Fig. 5. In the figure, gray, red, yellow, green, and blue represent the color centers with white, red, yellow, green, and blue background colors, respectively. The solid line represents the color center with high luminance level, and the dashed line represents the color center with low luminance level. Compared with Fig.2, it can be observed that CCM is difficult to distinguish different color centers in three channels. In the achromatic channel, the fitting result of the fixed-size stimuli fails to show its bandpass trend, while the fitting result of the fixed-cycle only indicates a slightly weak bandpass characteristics and fails to achieve effective prediction.

The contrast sensitivity prediction results of the fixed-size and fixed-cycle stimuli for 10 color centers using the optimized PCM are shown in Fig. 6. It can be observed that there is no significant difference in contrast sensitivity between two luminance levels of color centers with the same background color in three channels. This optimization result is consistent with expectations. The difference in contrast sensitivity data between two luminance levels is not obvious, which makes it difficult for the model to distinguish between these two luminance levels. In the achromatic channel, when the spatial frequency is low, there are significant differences in contrast sensitivity among various color centers, but the differences gradually decrease as spatial frequency increases; while in the R-G and Y-B channels, there is no significant change in contrast sensitivity differences among various color centers as spatial frequency changes; at the same time, the influence of color centers on contrast sensitivity in red-green channel is lower than that in other two channels, which may be due to higher overall contrast sensitivity threshold in red-green channel. Compared with the original contrast sensitivity data (Fig. 2), it can be observed that the difference in contrast sensitivity between various color centers on each channel predicted by the model is small, especially in red-green channel.

Table 3 shows the prediction error of the cone contrast model with the original parameters and two optimized models. Due to the different experimental task, the parameters of the original cone-contrast model were modified before calculating the error. Both two optimized models predicted more accurate than that of the original model, and the errors are lower than inter-observer variation.

The prediction accuracy of the optimized PCM is significantly higher than that of the optimized CCM. It is recommended to use the optimized PCM to predict the contrast sensitivity of two stimulus patterns under different color backgrounds, brightness levels, and spatial frequencies. Table 4 lists the optimized PCM parameters.

Conclusion

An experiment was conducted to study the contrast sensitivity of different color directions, stimulus patterns and spatial frequencies for 5 color centers, i.e., white, red, yellow, green and blue at two luminance levels for each color center. The present data showed a band-passed shape for achromatic contrast sensitivity function and a low-pass shape for R-G and Y-B contrast sensitivity functions. The fixed-size stimuli (much more than 2 cycles) had larger contrast sensitivities than the fixed-cycles stimuli (fixed 2 cycles). The brighter color centers had larger contrast sensitivities than those of the darker ones. The results were used to fit the cone-contrast model and postreceptoral-contrast models proposed by Mantiuk et al. The optimized models gave an accurate prediction of contrast sensitivity at different spatial frequencies. The optimized postreceptoral-contrast model shows better prediction accuracy than the optimized cone-contrast model. Also, it gave a higher predictive accuracy than the inter-observer variation.

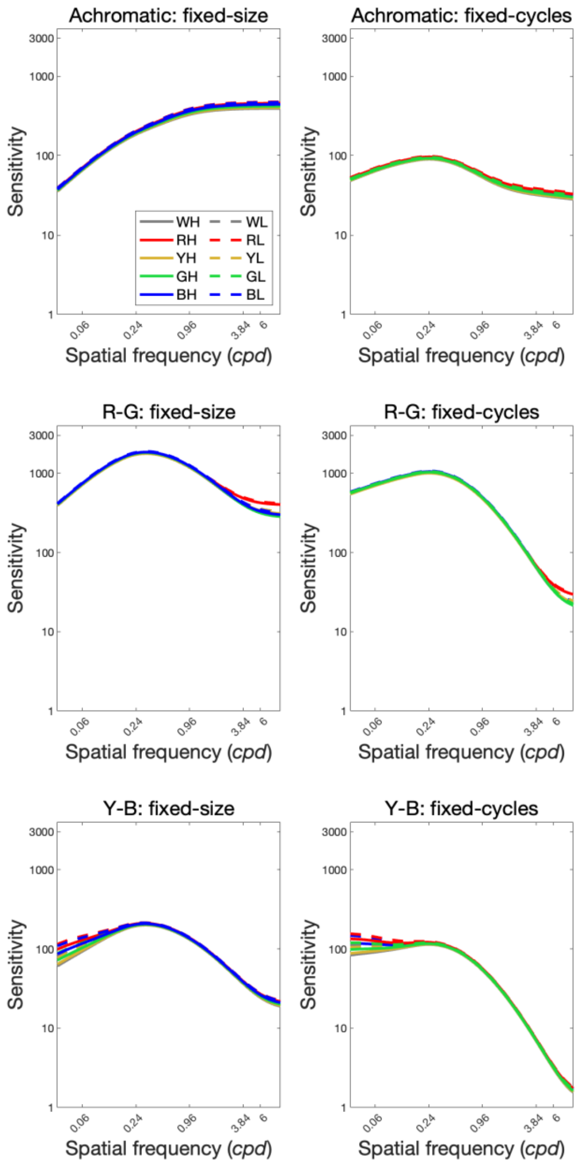

Figure 5. *Diagram of the prediction results of two stimulus patterns for different color centers using the optimized cone-contrast model.*

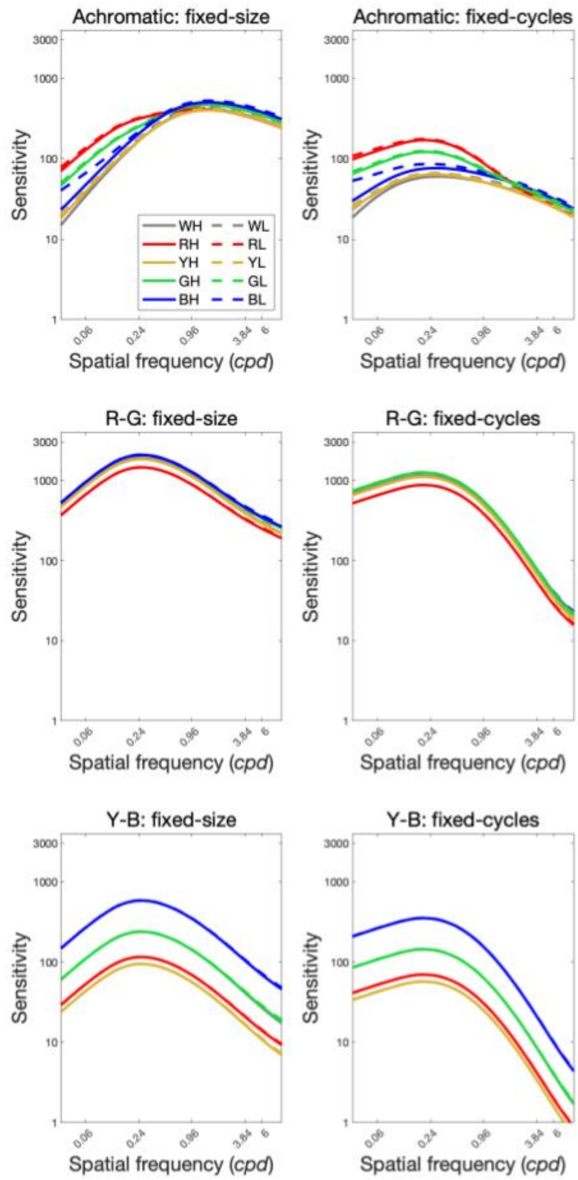

Figure 6. *Diagram of the prediction results of two stimulus patterns for different color centers using the optimized postrecpetoral-contrast model.*

Table 3. Model's error after (optimized) and before (original) optimization together with Inter-observer variation (Inter) in dB units

	Model prediction error												Inter-observer variation
	Original cone contrast model				Optimized cone contrast model				Optimized postreceptoral contrast model				
Colour centre	A	R-G	Y-B	Total	A	R-G	Y-B	Total	A	R-G	Y-B	Total	
WHfs	9.6	16.7	9.6	12.4	3.4	4.1	3.2	3.6	2.5	3.7	2.1	2.8	4.8
WLfs	10.1	10.0	2.9	8.4	3.1	2.7	2.0	2.7	2.1	2.2	1.7	2.0	4.8
RHfs	15.6	7.5	5.2	10.4	5.3	2.4	3.9	4.0	4.3	1.6	3.0	3.2	6.5
RLfs	19.2	11.2	11.0	14.3	7.8	5.8	7.8	7.2	6.0	3.2	2.4	4.1	4.8
YHfs	8.7	13.1	5.0	9.5	2.7	2.5	2.3	2.5	1.8	2.3	6.0	3.9	5.1
YLfs	12.7	10.1	3.1	9.5	6.3	2.8	3.2	4.3	5.6	2.7	6.4	5.1	6.4
GHfs	11.1	12.7	7.4	10.6	7.4	4.1	4.2	5.4	6.7	2.8	3.4	4.6	7.6
GLfs	14.5	8.7	3.6	10.0	6.8	3.8	3.3	4.9	6.5	3.0	3.6	4.6	6.9

BHfs	13.1	10.1	5.5	10.1	5.3	4.3	5.0	4.9	4.2	3.2	4.4	4.0	6.3
BLfs	16.4	4.7	3.7	10.1	5.7	1.0	4.6	4.3	5.1	0.9	5.8	4.5	5.3
WHfc	7.6	16.5	4.4	10.8	4.3	3.6	2.3	3.5	3.4	2.8	1.6	2.7	4.0
WLfc	10.3	7.0	8.4	8.7	3.3	1.0	2.4	2.4	2.4	1.6	3.5	2.6	8.7
RHfc	14.2	7.4	15.6	12.9	5.8	5.9	7.2	6.3	6.8	4.2	3.2	5.0	5.5
RLfc	15.0	11.0	20.3	15.9	4.9	7.6	9.9	7.7	5.5	5.9	5.0	5.5	8.7
YHfc	8.0	14.0	7.4	10.2	3.4	2.2	4.3	3.4	2.6	1.5	3.4	2.6	4.7
YLfc	9.6	10.8	12.3	11.0	3.3	3.4	7.3	5.0	2.3	2.8	2.5	2.5	5.7
GHfc	8.5	12.8	6.7	9.7	2.5	3.4	2.5	2.8	2.9	1.9	3.3	2.8	4.8
GLfc	11.2	3.1	10.8	9.2	3.9	4.1	4.5	4.2	4.7	5.6	5.6	5.3	5.3
BHfc	8.0	13.4	4.1	9.3	3.4	8.2	10.0	7.7	2.6	6.9	3.8	4.8	4.9
BLfc	10.2	4.8	3.2	6.7	3.4	5.2	8.2	5.9	3.0	4.2	5.9	4.5	6.1
Total	12.1	10.9	8.8	10.7	4.8	4.3	5.5	4.9	4.4	3.5	4.1	4.0	5.8

Table 4: Model parameters

$M_{LMS\text{-}ARB}$	$\begin{bmatrix} 1.000 & 4.911 & 2.687 \\ 1.000 & -2.688 & 4.670 \\ -0.607 & -1.593 & 1.000 \end{bmatrix}$
p	1.717
$s_{A1}, \ldots, s_{A5}$	209.058, 22.315, 0.005, 1002.801, 0.031
s_{R1}, s_{R2}, s_{R3}	1389.350, 57.861, 0.0041
s_{B1}, s_{B2}, s_{B3}	1134.557, 2.061, 0.917
$\rho_{A1}, \rho_{A2}, \rho_{A3}$	0.546, 2.516, 0.038
ρ_R, ρ_B	0.117, 0.0038
b_A, b_R, b_R	3.568, 2.253, 3.269
$\gamma_A, \gamma_R, \gamma_B$	2.440, 2.218, 2.218
$\hat{a}_A, \hat{a}_R, \hat{a}_B$	123.090, 30.599, 20.126
$\hat{f}_A, \hat{f}_R, \hat{f}_B$	3.370, 2.218, 2.204

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