https://doi.org/10.2352/issn.2169-2629.2019.27.59

Measurement of CIELAB spatio-chromatic contrast sensitivity in different spatial and chromatic directions

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Abstract

This paper presents data on CIELAB chromatic contrast sensitivity collected in a psychophysical experiment. To complement previously published data in the low-frequency range, we selected five spatial frequencies in the range from 2.4 to 19.1 cycles per degree (cpd). A Gabor stimulus was modulated along six chromatic directions in the a-b* plane. We also investigated the impact on contrast sensitivity from spatial orientations – both vertically and diagonally oriented stimuli were used. The analysis of the collected data showed lowest contrast sensitivity in the chromatic direction of around 120° from the positive a*-axis. The contrast sensitivity in the diagonal spatial orientation is slightly lower when compared to the vertical orientation.*

Introduction

The research in human vision has placed a lot of effort in measuring and explaining spatial contrast sensitivity of different target stimuli in different viewing conditions. The contrast sensitivity is commonly defined as the inverse of a just perceptible contrast of a target stimulus. It is measured in a psychophysical experiment, normally for several discrete spatial frequencies of the target stimulus so that a contrast sensitivity function (CSF) can be fitted over the whole range of spatial frequencies. The CSF can be used in simplistic linear models of the human visual system (HVS) in a wide range of applications, including image quality [1], image compression [2], image synthesis [3], or image watermarking [4].

Human color perception starts from the three types of photoreceptors – the L, M, and S cones in the retina. It is generally accepted that, in the early processing of neural responses from the cones, an opponent-color three-channel encoding is employed, resulting in one achromatic channel carrying intensity information, and two chromatic opponent channels (red-green and blue-yellow). The contrast sensitivities of the three channels has been measured in many different studies. The achromatic CSF has a band-pass shape for different background luminance [5]. The chromatic CSF (CCSF) has been measured mostly in the two cardinal chromatic directions (red-green and blue-yellow); the shape is low-pass, and the sensitivity in the red-green channel is higher than the sensitivity in the blue-yellow channel [6].

A CCSF is affected by more parameters than an achromatic CSF because of the higher color-dimensionality. The chromatic direction is an important parameter – there can be many directions in a chromatic 2D plane. Another important CCSF parameter is the color space used for modulating and measuring the perceptibility of a chromatic grating, which is closely tied to the chromatic direction. The background adapting color (luminance and chromaticity) is another important parameter of the CCSF. As in the achromatic case, the shape of the chromatic grating, its size and spatial orientation have impact on the CCSF. The brief review of published work on CCSF that follows is presented in terms of the above-mentioned parameters. Mullen measured CCSF in the red-green and blue-yellow directions [6]. The chromatic gratings were realized by directly modulating the phosphors of a CRT monitor, so the CCSF values are expressed using luminance variation of each phosphor separately. The CCSF was measured for a horizontal sinusoidal grating placed on a gray background, in the range of 0.1 - 7 cycles per degree (cpd). Rajala et al. measured the CCSF in the two cardinal directions of the x-y chromaticity diagram [7]. The chromatic sinusoidal stimuli were modulated on a gray background, in four different spatial orientations, in the range of 0.5-20 cpd. It was demonstrated that the sensitivity in the diagonal directions is somewhat lower than the one in the horizontal or vertical spatial directions. Owens et al. measured the CCSF in four chromatic directions of the LMS-cone space and for different background adapting colors [8]. The sinusoidal stimuli were horizontally oriented, ranging from 2.5 to 29 cpd. It was found that the sensitivity in certain chromatic directions can vary with the background color. Kim et al. measured the CCSF in the two cardinal directions of the LMS-cone space for different luminance levels of the gray background [9]. The sinusoidal stimuli were horizontally oriented, covering the frequency range 0.25 – 8 cpd. It was found that chromatic sensitivity increases with background luminance but saturates at around 40 cd/m^2. Lin et al. measured the red-green CCSF in the CIELAB space for frequencies between 0.1 and 25 cpd [10]. The chromatic grating was square-wave unlike the previous studies that used sinusoidal grating. The authors also proposed a CIELAB-based formula for chromatic contrast. Lucassen et al. measured the CCSF in four chromatic directions of the CIELUV color space at three different yellowish background colors [11]. The chromatic stimuli were sinusoidal in the range of 0.15 – 5 cpd. They showed that the size and therefore the number of cycles in the chromatic stimulus may affect the contrast perceptibility threshold at very low spatial frequencies. Xu et al. measured the CCSF in the CIELUV color space along six chromatic directions at two different background colors [12]. They used horizontal and vertical spatial orientations for the chromatic stimuli, and covered the low frequency range of 0.06 – 3.84 cpd. Their results showed that the HVS is least sensitive to a chromatic modulation oriented at around 120° from the positive a*-axis in the CIELAB color space.

This paper aims to provide measurements of spatial chromatic contrast sensitivity in several chromatic directions of the CIELAB color space. Regarding the similar recent study [12], this paper aims to provide complementary data by covering higher spatial frequencies. In this work, we also investigate the impact of spatial orientation on the chromatic contrast sensitivity. For this purpose, a psychophysical experiment is conducted for collecting chromatic contrast perceptibility thresholds. It is described in the next section, followed by analysis of the collected data.

Psychophysical experiment

This section describes the setup and the methodology used in the psychophysical experiment for collecting thresholds of just noticeable chromatic grating. The choice of the experiment settings was made with the prospects of using the collected thresholds for visibility models in printing reproductions; therefore, we followed guidelines from the ISO 12646:2015 standard for display characterization for soft-proofing [13].

Equipment

The experiment was conducted on a 10-bit EIZO ColorEdge CG248-4K 24” display at its native resolution of 3840×2160 pixels. The 10-bit workflow was ensured by using the PsychToolbox [14] that enables 10-bit frame buffers via OpenGL, and the NVIDIA Quadro K620 graphic card that supports 10-bit output per color channel. Thus, the total number of possible displayed colors is 2^{30}. The white point of the display was set to a D50 chromaticity at 160 cd/m^2 luminance. The gamma of the display was set to 2.2. The display was calibrated using a third-order polynomial transform between the device RGB values and the displayed XYZ tristimulus. The third-order polynomial transform included all possible terms (including cross-products), and it was obtained by least-squares fitting from 343 training patches uniformly-spaced in RGB and measured with an XRite i1 Pro spectrophotometer. We used the color engineering toolbox for fitting the polynomial transform [15]. The calibration accuracy for color patches with luminance above 10 cd/m^2, in terms of average and maximum CIEDE2000 color difference, was 0.25 and 1.53, respectively.

Stimuli

The color space for modulation of the chromatic stimuli was chosen to be the CIELAB space, as the collected contrast thresholds would have a practical value due to the wide use of CIELAB in the industry. The background (base) color was set to a gray color with CIELAB value of [50, 0, 0]. The luminance of the gray background was 32.7 cd/m^2. The chromatic stimuli are vertical Gabor stimuli i.e. sinusoidal gratings multiplied by a 2D Gaussian window. The size of the stimuli was chosen such that the area within one standard deviation from the maximum of the 2D Gaussian corresponds to a 2° angle subtended at the observer’s retina. The Gabor stimuli were generated at five different spatial frequencies: 2.4, 4.8, 7.6, 12.7, and 19.1 cpd. The exact choice of spatial frequencies was made so that it ensures proper sampling of the sinus function – the periods are of even pixel-length (32, 16, 10, 6, 4 pixels) and both sinus extremes are always included in the discrete sequence. The stimuli were generated along six chromatic directions in the a*-b* CIELAB plane. The six chromatic angles, with respect to the positive a*-axis, are: 0°, 30°, 60°, 90°, 120°, and 150°. Along these chromatic directions, the strength of the chromatic modulation was varied in terms of Δab that is the Euclidean distance between the background color and the furthest stimulus point in the a*-b* chromatic plane. An example of the chromatic stimuli used in the experiment is shown in Figure 1.

Given that prior work showed no significant difference in the CCSF between horizontal and vertical orientation, as well as between the two diagonal orientations [7], we used only vertical spatial orientation, and one diagonal orientation (vertical rotated for 45° clockwise). In order to avoid resampling distortions, the diagonal stimuli were not calculated digitally, but they were realized using the same vertical stimuli on a 45° rotated display.

Figure 1. *Vertical Gabor stimuli modulated at six CIELAB chromatic directions with equal Δab contrast. Top row: 0°, 30°, and 60°. Bottom row: 90°, 120°, and 150°. Best viewed in the electronic version of this article.*

Contrast units

There are no well-standardized formulas for calculating chromatic contrast, as it is in the grayscale case. For example, the contrast can be expressed as a CIEDE2000 color difference [16], as a Euclidean distance in the particular color space [11,12], or using a more complex ratio [10] in order to resemble the Michelson contrast formula. In this work, we express the contrast thresholds in terms of the maximal amplitude of the Gabor grating i.e. it is the Euclidean distance Δab between the non-modulated background and the furthest chromatic point of the Gabor stimuli.

Procedure

Fifteen observers participated in the experiment, of which ten males and five females, aged between 22 and 36. All observers had normal color vision and normal or corrected to normal visual acuity. The stimuli were observed in a dark room from 60cm viewing distance. Prior to the experiment, the observers spent at least two minutes to adapt to the D50 white point of the display and the dark surrounding, and at least two minutes to adapt to the background color and luminance used in the experiment. A black cardboard with circular opening in the center was placed in front of the display. The black cardboard was large enough to cover the monitor and remove external visual cues about orientation. The circular opening covered only the displaying area, its diameter was 26.8° visual degrees, and the chromatic stimuli were displayed in the central area of the effectively circular display. This setup was similar to that used by Amirshahi et al. [17].

The thresholds for all spatial frequencies and chromatic directions were collected in a single session for a given spatial orientation of the stimuli. The observer’s input was collected using the four-alternative-forced-choice (4AFC) method: in one of the four possible fixed areas (in a spatial 2×2 arrangement) that was randomly chosen, a chromatic stimulus at randomly chosen test frequency and randomly chosen chromatic direction was displayed; the observer was supposed to click on one of the four areas that contained the chromatic stimulus. The contrast thresholds were estimated after 30 trials of the QUEST adaptive staircase method [18]. We used the PsychToolbox implementation of the QUEST method. Based on the observer’s response (correct or wrong click), the QUEST method was used to select the testing contrast in the next trial. A marker tone sounded at the beginning of the presentation of every new stimulus. The time for a single response was not limited; however, observers were instructed to make a choice on average every 3-4 seconds in order to keep the experiment session around one hour (30 trials × 5 frequencies × 6 chromatic directions × 4 seconds = 60 minutes). All observers completed two sessions, one for vertical spatial orientation and another for the diagonal orientation using 45° rotated display. All sessions were completed in between 50 and 75 minutes; the total experiment time for all observers was around 32 hours.

Results

Combining the chromatic directions, spatial frequencies, and spatial orientations, resulted in 60 different contrast thresholds that were measured for each observer. The thresholds are expressed in terms of Δab – the largest amplitude (both positive and negative) of the Gabor stimuli. They are calculated as the average from all observers. Figure 2 shows the collected contrast thresholds using the vertical Gabor stimuli (the actual averaged thresholds are shown with stars). In order to estimate the contrast thresholds for all chromatic directions, we fitted ellipses in a least squares error manner using the thresholds for each spatial frequency. From Figure 2 it can be seen that, except for the highest frequency, the ellipses are tilted at nearly same angle. This angle approximates the direction along which the chromatic CIELAB contrast thresholds are highest. Figure 3 shows the average measured contrast thresholds along with the fitted ellipses for the diagonal stimuli. The same trend in the fitted ellipses can be observed: they are tilted at nearly the same angle as the ellipses in Figure 2. The exact angles of tilt are given in Table 1. Apart from the highest spatial frequency, all other angles are close to 120° - which is what was observed in a previous study on CIELAB chromatic contrast sensitivity in lower spatial frequencies [12]. The contrast sensitivity values, calculated as inverse values of the Δab contrast thresholds, are given in Figure 4 and Figure 5, for the vertical and diagonal stimuli, respectively. The 95% confidence intervals, at each of the measured thresholds, are marked with '×'. As expected, the chromatic contrast sensitivity has a decreasing tendency with spatial frequency, for all six chromatic directions. The plots in Figures 4 and 5 give another illustration regarding the chromatic direction of highest thresholds i.e. lowest contrast sensitivity - the CCSF values for the measured chromatic angle of 120° are noticeably lower. However, at the highest measured frequency, the relative difference in contrast sensitivity between the different chromatic directions is very small.

Regarding the difference in contrast sensitivity between the two spatial orientations, we calculated the average threshold difference between the diagonal and vertical orientation. The results are given in Table 2. It can be seen that, except for one, the difference is positive for all other testing conditions, i.e. the thresholds for the diagonal orientation are higher on average.

Table 1. Angles of tilt of fitted ellipses

	2.4 cpd	4.8 cpd	7.6 cpd	12.7 cpd	19.1 cpd
Vertical stimuli (Figure 2)	122.0°	118.7°	114.2°	115.4°	135.1°
Diagonal stimuli (Figure 3)	117.1°	119.0°	113.4°	114.7°	144.6°

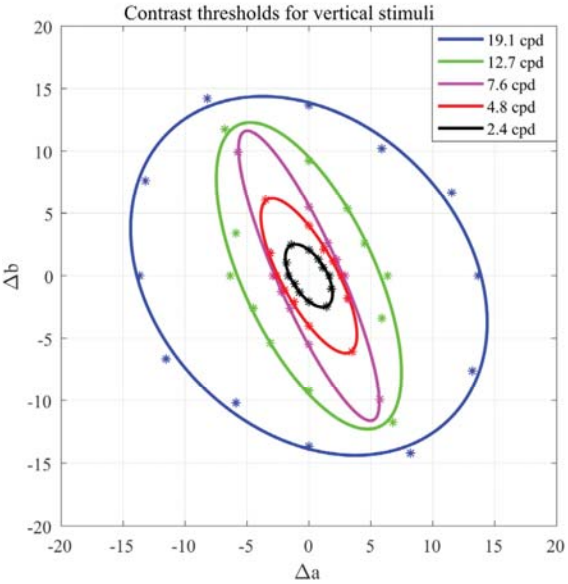

Figure 2. Contrast thresholds for the vertically oriented stimuli at different spatial frequencies. The actual measured thresholds are shown with stars, along with the fitted ellipses.

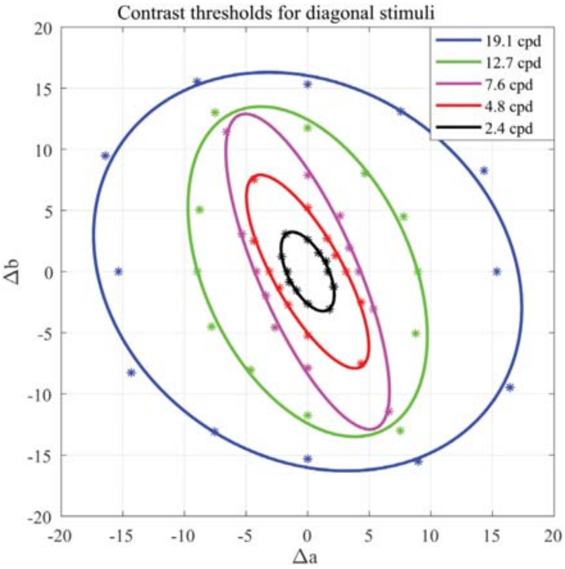

Figure 3. Contrast thresholds for the diagonally oriented stimuli at different spatial frequencies. The actual measured thresholds are shown with stars, along with the fitted ellipses.

Table 2. Average threshold (Δab) difference between diagonal and vertical spatial orientation

	2.4 cpd	4.8 cpd	7.6 cpd	12.7 cpd	19.1 cpd
0°	-0.03	0.49	1.23	2.59	1.69
30°	0.41	0.35	1.33	3.81	3.21
60°	0.25	0.73	2.24	3.06	3.34
90°	0.54	1.22	2.38	2.55	1.66
120°	0.70	1.70	1.74	1.46	1.53
150°	0.34	1.41	2.40	3.32	3.71

The threshold increase for the diagonal orientation is statistically significant (at 95% confidence) for 25 of the 30 different combinations in Table 2. For the significance testing, we used one-sided paired t-test of the null hypothesis: the average thresholds for diagonal orientation are not higher than the average thresholds for vertical orientation. If the difference is aggregated for each spatial frequency, then the threshold increase is significant for all five frequencies. This is demonstrated with the results from the t-tests in Table 3; the 95% confidence interval does not include zero so there is a significant threshold increase for all spatial frequencies.

An important aspect of chromatic sensitivity measurement is the requirement for the stimuli to be of constant luminance. Previous work has used standard observer isoluminance [7, 9, 11, 12], or individualized isoluminance, i.e. calibrated for each observer [6, 8, 10]. In this work, we used chromatic stimuli isoluminant to the standard observer, i.e. having a constant Y (or L*) value. The accuracy of calibration was measured with a Konica Minolta CS-2000 spectroradiometer; the standard deviation of the luminance in the a*-b* plane of our chromatic stimuli was $\Delta Y=0.24$ cd/m^2 (or $\Delta L^*=0.16$). The luminance deviation across the a*-b* plane was not noisy but rather monotonic – most likely due to the smooth 3rd order polynomials used for the XYZ to RGB characterization. As a result, the luminance deviation was larger between further points of the a*-b* plane, so it had a higher impact on the measurement of the higher thresholds. However, we believe this impact was small, and did not affect the general conclusions regarding the chromatic angle of lowest sensitivity and the sensitivity difference between the vertical and diagonal orientation.

Conclusion

In this work, we study the chromatic contrast sensitivity in the CIELAB color space. A psychophysical experiment was conducted to collect contrast perceptibility thresholds for six different chromatic modulations in the a*-b* plane, five spatial frequencies, and two spatial orientations. It was found that the contrast sensitivity reaches a minimum around the chromatic direction that is 120° from the positive a*-axis. The spatial orientation was found to have an impact on the contrast perceptibility thresholds - the results showed that there is a small but significant threshold increase for most of the frequency-chromaticity combinations.

Investigating the chromatic contrast sensitivity using stimuli modulated at different non-neutral background colors would be a possible extension of this work. In recent works on chromatic contrast sensitivity, yellow [11] and green [12] color centers have been used. Measuring the CCSF at different color centers across the gamut would be color-space specific but would enable more accurate models of the chromatic contrast sensitivity.

Table 3. Results of the t-tests for the thresholds increase in the diagonal orientation, aggregated for each frequency

	2.4 cpd	4.8 cpd	7.6 cpd	12.7 cpd	19.1 cpd
Average threshold increase	0.37	0.98	1.88	2.80	2.52
Lower value of the 95% conf. interval	0.16	0.54	1.45	2.13	1.70
Null hypothesis rejected	yes	yes	yes	yes	yes

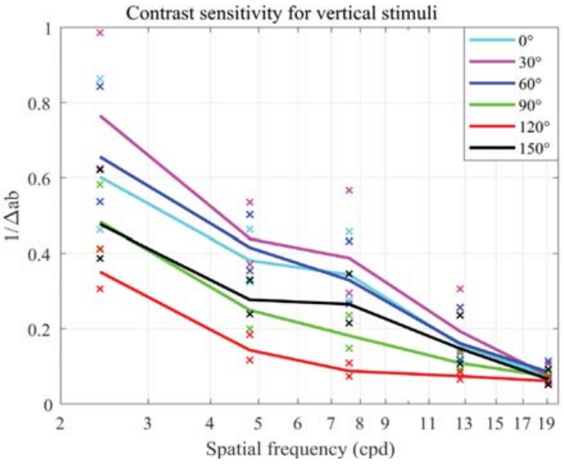

Figure 4. Contrast sensitivity for the vertically oriented stimuli at the six (color-coded) chromatic directions. The 95% confidence intervals at each measured spatial frequency are marked with '×'.

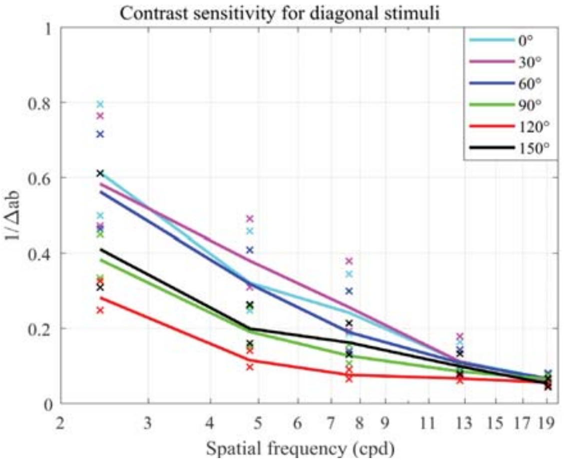

Figure 5. Contrast sensitivity for the diagonally oriented stimuli at the six (color-coded) chromatic directions. The 95% confidence intervals at each measured spatial frequency are marked with '×'.

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Alastair Reed received his B.Sc degree in Physics from Imperial College, London in 1975 and a Ph.D. in Physics from the University of North London in 1979. He went on to do color image processing for 5 years at Crosfield Electronics in Hemel Hempstead, England and 12 years at Cymbolic Science International in Richmond, Canada before coming to Digimarc in Portland, Oregon 20 years ago. Alastair is a Principal R&D Engineer at Digimarc and his work has involved modeling the human visual system and the print process, to reduce watermark visibility.

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Marius Pedersen is professor at the Norwegian University of Science and Technology. His work is centered on image quality assessment; he has more than 60 publications in this field. He received his PhD in color imaging (2011) from the University of Oslo. He is currently the head of the computer science group in Gjøvik in the department of computer science, and the head of the Norwegian Colour and Visual Computing Laboratory, both at NTNU.