

# Measurements of achromatic and chromatic contrast sensitivity functions for an extended range of adaptation luminance

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## ABSTRACT

Inspired by the ModelFest and ColorFest data sets, a contrast sensitivity function was measured for a wide range of adapting luminance levels. The measurements were motivated by the need to collect visual performance data for natural viewing of static images at a broad range of luminance levels, such as can be found in the case of high dynamic range displays. The detection of sine-gratings with Gaussian envelope was measured for achromatic color axis (black to white), two chromatic axes (green to red and yellow-green to violet) and two mixed chromatic and achromatic axes (dark-green to light-pink, and dark yellow to light-blue). The background luminance varied from 0.02 to 200 cd/m<sup>2</sup>. The spatial frequency of the gratings varied from 0.125 to 16 cycles per degree. More than four observers participated in the experiments and they individually determined the detection threshold for each stimulus using at least 20 trials of the QUEST method. As compared to the popular CSF models, we observed higher sensitivity drop for higher frequencies and significant differences in sensitivities in the luminance range between 0.02 and 2 cd/m<sup>2</sup>. Our measurements for chromatic CSF show a significant drop in sensitivity with luminance, but little change in the shape of the CSF. The drop of sensitivity at high frequencies is significantly weaker than reported in other studies and assumed in most chromatic CSF models.

**Keywords:** CSF, Contrast sensitivity function, high dynamic range, luminance masking, chromatic CSF

This version of the paper contains important corrections that had been made after the paper was published in the SPIE digital library. The digital library versions has the data incorrectly scaled in Figs. 2–8.

## 1. INTRODUCTION

The contrast sensitivity functions (CSFs) are one of the main components of visual models and metrics. Most models of CSFs were developed based on the data from numerous historical psychophysical experiments. However, the models derived from such data suffer from several problems. Firstly, quite often the data from several distinct experiments had to be combined to cover the required range of spatial frequencies and luminance levels. Therefore, the data for different range of conditions could be inconsistent because it was measured for different individuals, different stimuli or experimental conditions. Secondly, the data was often collected using artificial viewing conditions, such as dilated and artificial pupils, flickering stimuli, narrowband light or the stimuli that was compensated for the effect of chromatic aberrations of the eye.<sup>1</sup> Such conditions are unlikely to be found in typical viewing scenarios, where CSF models are meant to be used.

The ModelFest<sup>2</sup> and ColorFest<sup>3</sup> datasets were collected in an effort to build a general detection model of an average observer and to address the limitations of the historical data. However, those data sets have a major limitation that all stimuli were shown at a single background luminance.

In this study, we conducted the experiments for both achromatic and chromatic CSFs for a wide range of adapting luminance levels, inspired by the measurements made for the ModelFest and ColorFest data set. We created sine-grating stimuli for achromatic CSF (black to white) and two chromatic CSFs (green to red and

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yellow-green to violet) and two mixed chromatic and achromatic CSFs (dark-green to light-pink, and dark yellow to light-blue) while varying the background luminance levels from 0.02 to 200 cd/m<sup>2</sup>. The frequency range of the sine gratings varied from 0.125 to 16 cpd (cycles per degree). More than four observers participated in the experiments and they individually determined the detection threshold for each stimulus using 20 trials of QUEST method.<sup>4</sup>

The results of our achromatic CSF measurements, together with a model explaining the data, were reported elsewhere.<sup>5</sup> This paper extends the discussion of the data, reports the data for individual observers and also presents the results of the new measurements for chromatic, and mixed chromatic and achromatic CSF.

## 2. RELATED WORKS

### 2.1 Achromatic CSF

The achromatic CSFs have been measured in a number of studies. An excellent review of these measurements can be found in Barten.<sup>6</sup> One study that covered the largest range of conditions and is thus the closest to our measurements, is that of Meeteren and Vos.<sup>7</sup> The measurements extended a wide range of luminance from 0.0001 to 10 cd/m<sup>2</sup> and the range of frequencies from 0.5 to 30 cpd. Our measurements extend into higher luminance levels (150 cd/m<sup>2</sup>), which are more relevant for photopic vision, and also lower frequencies, down to 0.125 cpd. Such low frequencies are necessary to observe and model the band-pass characteristic of CSF, especially for low luminance levels. The field size of the stimuli used in the Meeteren and Vos experiment was relatively large, extending 17 x 11 deg. Such large fields pose problems when they need to be represented as images in visual models. Their measurements were collected for only 2 observers.

A number of analytical CSF models have been proposed in the literature to explain the collected data. However, the vast majority of these models accounted for the effect of frequency alone. The second factor that has the highest effect on the detection threshold is luminance. The effect of luminance was modelled in two comprehensive CSF models, one proposed by Barten<sup>6</sup> and another by Daly.<sup>8</sup> Both CSF models rely on complex analytical formulas, which are fitted to the data reported in the literature. Barten's model is a meticulously derived composition of more basic models contributing to the detection process. These include optical transfer function and psychometric function. Barten's model was shown to predict many historical CSF measurements. However, its main weakness is that it is valid only for photopic (cone-mediated) vision. Fewer details are known about the derivation of the Daly's model and only the final formula is reported.<sup>8</sup>

### 2.2 Chromatic CSF

There have been several studies measuring chromatic CSFs,<sup>1,9-12</sup> however we could not find the data that would cover the wide range of luminance levels. Similarly as in case of achromatic CSF, the conditions used for some of these measurements were not consistent with the goal of visual models and metrics. We briefly explain the previous research on chromatic CSFs.

Green<sup>9</sup> measured the CSFs at different luminance levels where coloured sine-grating was shown on a background of different color. No effort was made to produce isoluminant patterns and hence the resulting CSFs had a band-pass shape typical for achromatic CSF. This is in contrast to modern chromatic CSF measurements, which attempt to stimulate only chromatic mechanisms of the visual system. The viewing conditions were strictly controlled but were also atypical of the normal viewing: artificial and dilated pupil, monocular viewing, the stimuli was corrected for chromatic aberrations with lens.

Granger and Heurtley<sup>10</sup> measured red-green chromatic CSF with yellow background at 85 trolands (27 cd/m<sup>2</sup>) over the range 0.125–20 cpd. They reported low-pass characteristic of the CSF, consistent with the data of van der Horst and Bouman.<sup>13</sup> But they also observed that high-frequency patterns are seen as achromatic (black to white), rather than color modulations. When the detection criterion was the recognition of color, a narrower spatial frequency band-pass was measured. We observed the same phenomenon in our measurement, however we used the detection as a criterion.

The chromatic CSFs from Mullen's 1985 paper<sup>1</sup> have been widely used in color visual models.<sup>14,15</sup> However, this data is not representative as a model of an average observer. The experiment was designed to discard the

effect of chromatic aberration in the eye while such aberration actually happens when perceiving normal scenes. In addition, they measured the chromatic CSFs only at a single luminance level.

Hirai et al.<sup>12</sup> measured achromatic spatio-velocity (SV) CSF at 100 cd/m<sup>2</sup> and two chromatic SV-CSF at 38.5 cd/m<sup>2</sup> for red to green and at 12.2 cd/m<sup>2</sup> for blue to yellow, all in the range 0.5–8 cpd. The data was used to model chromatic spatio-velocity contrast sensitivity. The model was then used to extend the sCIELab quality metric<sup>16</sup> to the temporal domain. Because of the application, the stimuli was observed in natural conditions. Flicker photometry was used to find isoluminant chromatic axes. The data is quite consistent with our measurements, but it was measured for a single luminance level.

### 3. EXPERIMENT DESIGN

#### 3.1 Stimuli

The stimuli design was inspired by the ModelFest and ColorFest data sets. The stimuli consisted of vertical sine-gratings attenuated by a Gaussian envelope. The standard deviation of the Gaussian was equal to 1.5 visual degree for all stimuli except for the lowest frequency of 0.25 cpd for chromatic and mixed chromatic stimuli (C2, C3, C6 and C7), where the standard deviation was equal to 3 visual degrees. The background luminance varied from 0.02 to 200 cd/m<sup>2</sup>. The luminance levels were selected to make the best use of the colour gamut of the display and to avoid luminance levels lower than 10 cd/m<sup>2</sup>, at which the color calibration was unreliable. The luminance levels below 10 cd/m<sup>2</sup> were achieved by wearing modified welding goggles in which the protective glass had been replaced with neutral density filters (Kodak Wratten Gelatin) with either 1.0D, 2.0D densities, or both filters together to achieve 3.0D (1000 times light reduction). The frequency range of the sine gratings varied from 0.125 to 16 cpd for achromatic stimuli and from 0.25 to 8 for chromatic stimuli. Some combinations of frequencies and luminance levels were omitted from the measurements because they required producing stimuli of very high contrast that exceeded the color gamut of the display. Stimuli were observed with a natural pupil. The area of the screen outside the stimulus was set to the mean luminance level. The stimuli were created for five color directions, black to white, red to green, yellow-green to violet, dark-green to light-pink, and dark-yellow to light-blue, which are denoted as C1, C2, C3, C6, and C7 following the same convention as used in the ColorFest paper.<sup>3</sup> The detail of creation of the stimuli is described elsewhere.<sup>3</sup>

We found that the white-point reported for the Colorfest dataset appears very bluish. After converting the chromatic coordinates of the background color from the LMS to xyY color space, the white point has the coordinates  $x = .285$ ,  $y = .313$  which result in a color that is even more bluish than the illuminant D75. To make the color of the white point more consistent with the modern display neutral white, the von Kries transform was used to bring the background colour of all images to the color of the illuminant D65 (Table 1, Figure 1). It can be expected that this change will have a minor effect on the results because the chromatic adaptation mechanism of the visual system is likely to compensate for the reference white color. However, this background color change will affect the reported contrast values, as explained in Section 3.2.

In contrast to most CSF measurements, the stimuli were not modulated over time and the presentation time was not limited. This is because our goal was to collect the data for visual models that would apply to static images. It could be argued that the data for steady-viewing without temporal flicker better corresponds to the case when two complex images are compared side by side. To mask the onset of the stimuli, a white noise pattern of high contrast was shown just before and after the stimuli was shown.

#### 3.2 Contrast units

All data is reported in terms of sensitivity,  $S$ , which is defined as the inverse of the threshold contrast  $C$ :

$$S = \frac{1}{C} \quad (1)$$

For better visualization, the sensitivity is plotted using  $\log_{10}$  scale. The data for achromatic CSF is reported as a relative modulation of the sine-grating:

$$C = \frac{m}{L_b} \quad (2)$$

Table 1. The L, M, S cone excitations of the endpoints (From color and To color) of the color directions and of the background (D65) after correcting the white point of ColorFest paper.

<i>Colordirection</i>	<i>Background(D65)</i>			<i>From color</i>			<i>To color</i>		
	<i>L</i>	<i>M</i>	<i>S</i>	<i>L</i>	<i>M</i>	<i>S</i>	<i>L</i>	<i>M</i>	<i>S</i>
<i>C1(Black to white)</i>	26.19	13.81	0.35	24.88	13.12	0.33	27.50	14.50	0.37
<i>C2(Green to red)</i>	26.19	13.81	0.35	26.25	13.76	0.35	26.13	13.86	0.35
<i>C3(Yellow – green to violet)</i>	26.19	13.81	0.35	26.19	13.81	0.31	26.19	13.81	0.39
<i>C6(Dark – green to light – pink)</i>	26.19	13.81	0.35	25.76	13.62	0.31	26.62	14.00	0.39
<i>C7(Dark – yellow to light – blue)</i>	26.19	13.81	0.35	26.70	14.17	0.40	25.68	13.45	0.30

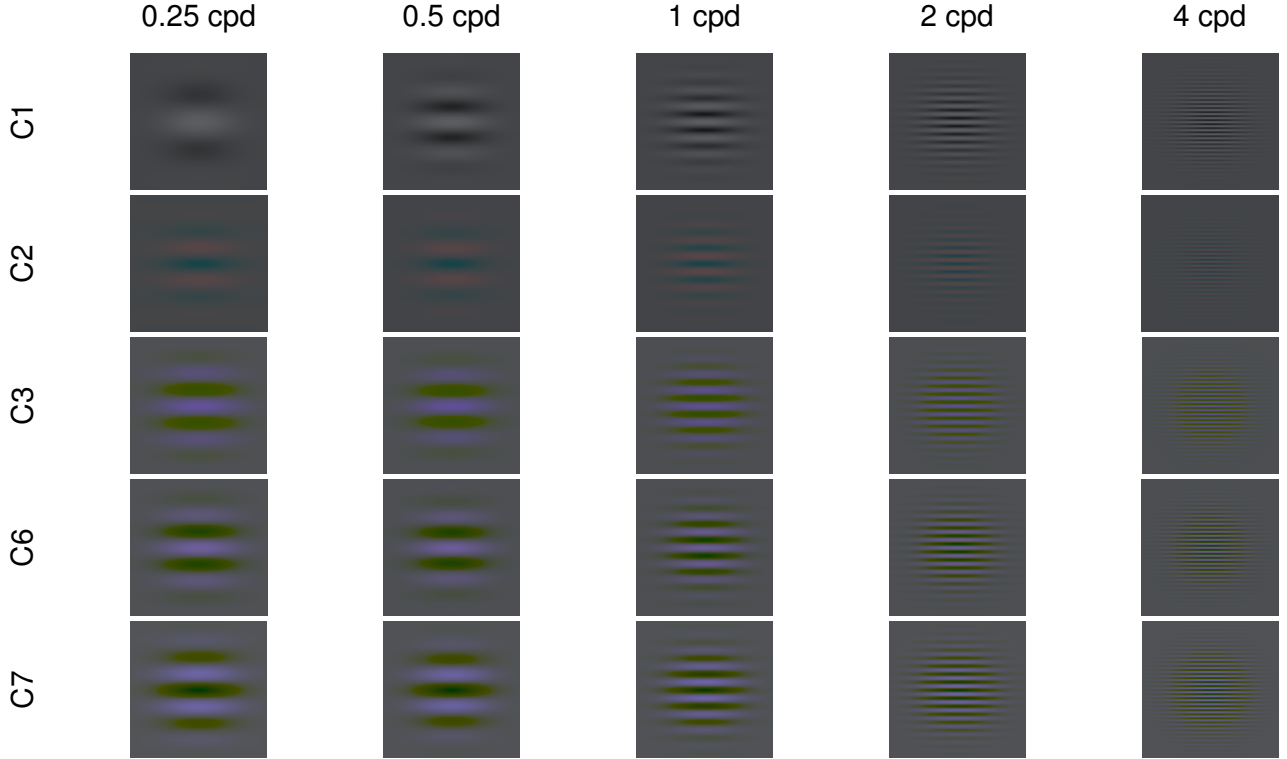


Figure 1. A subset of the stimuli used in our experiment.

where  $m$  is the amplitude of the sine grating and  $L_b$  is the luminance of the background. For chromatic CSF, we follow the contrast definition used for the ColorFest study<sup>3</sup> and compute it as:

$$C = \frac{1}{\sqrt{3}} \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta M}{M}\right)^2 + \left(\frac{\Delta S}{S}\right)^2} \quad (3)$$

where  $\Delta L|\Delta M|\Delta S$  are the modulations of the grating along L|M|S-dimensions of the LMS color space, and  $L|M|S$  are the LMS trichromatic color values of the background color.

The following transformation was used to convert from CIE 1931 Standard Observer color matching functions to the LMS cone response color space:<sup>17</sup>

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.15514 & 0.54312 & -0.03286 \\ -0.15514 & 0.45684 & 0.03286 \\ 0 & 0 & 0.00801 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \quad (4)$$

### 3.3 Display and viewing conditions

The experiments were run in two separate laboratories using two different displays: 26 NEC SpectraView 2690 (in Bangor University) and 24" HP LP2480sz (in Seoul National University). Both are high quality, 1920 x 1200 pixel resolution, LCD displays offering good color reproduction with a 10-bit LCD panel and RGB LED backlight. Additional two bits of bit-depth were simulated by spatio-temporal dithering, implemented on the graphics card using fragment programs. This gave the effective bit-depth resolution of 12-bits, which is necessary for near-threshold detection experiments. Stimuli were observed from a fixed distance of 93 cm, which gave an angular resolution of 60 pixels per visual degree. Only for the lowest frequency of 0.25 cpd for C2, C3, C6 and C7 we used much shorter viewing distance of 49 cm, which corresponds to the angular resolution of 32 pixels per visual degree. The displays were calibrated using a spectro-radiometer. The calibration accounted for the spectral emission characteristic of each display. The display white point was fixed at D65. The detail of calibration procedure is described in the subsequent section.

### 3.4 Display calibration

Since generating accurate luminance and color is crucial for the CSF experiments, extra care was taken to calibrate the displays used in the experiments. To model the relation between pixel values and colorimetric values, we used the gamma-offset-gain (GOG)<sup>18</sup> display model:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_{RGB \rightarrow XYZ} \begin{bmatrix} R^{\gamma_r} \\ G^{\gamma_g} \\ B^{\gamma_b} \end{bmatrix} + \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} \quad (5)$$

where  $[X Y Z]'$  are the trichromatic color values for the displayed color,  $M_{RGB \rightarrow XYZ}$  is the  $RGB \rightarrow XYZ$  transformation matrix,  $[R G B]'$  are pixel values and  $\gamma_r, \gamma_g, \gamma_b$  are gamma values of each individual color component.  $[X_B Y_B Z_B]'$  is the color of the black level. The transform matrix, the black level and the gamma values for each color channel were found by least-square fitting to the display measurements. The fit was good for both displays. Although a lookup table could potentially be more accurate than the *gamma* function we used, the measurement noise made the display response curve non-monotonic and therefore not suitable for a look-up table.

### 3.5 Experiment procedure

Seven observers participated in the measurements of the achromatic stimuli (C1: black to white) and six observers participated in the measurements of the chromatic stimuli (C2 and C3). In case of C1, four observers completed the experiment for all luminance levels and three observers for luminance of 2 cd/m<sup>2</sup> and higher. The measurements were repeated for selected observers or for those measurements that varied significantly from the averaged results.

The detection threshold of each stimulus was determined through at least 20 trials of the QUEST method.<sup>4</sup> In each trial, four-alternative-forced-choice (4AFC) method was used: four stimuli, of which three were reference images and only one was test image, were shown side-by-side on the same screen without restricting the presentation time. The observers were asked to choose which of the four stimulus contained the pattern. We found the 4AFC method faster converging than 2AFC because of the lower probability of correct guesses. Based on the observer's response, the QUEST method was used to find the degree of contrast for the next trial. The degree of contrast for the initial trial was determined using the method of adjustment, in which an observer was asked to adjust contrast of the shown pattern until it was barely visible. Each observer completed all the tests in 3-4 sessions of 30-45 minutes each. Details on the QUEST are described in the subsequent section.

### 3.6 QUEST

A number of methods are available for estimating the threshold of a stimulus and they can be largely divided into two categories:<sup>19</sup> constant-stimuli methods and adaptive procedures. In the constant-stimuli method, human responses for the visibility of a stimulus with different magnitudes (usually more than four or five) are collected and then the threshold of the stimulus is inferred from the collected results. The magnitudes of the stimulus are

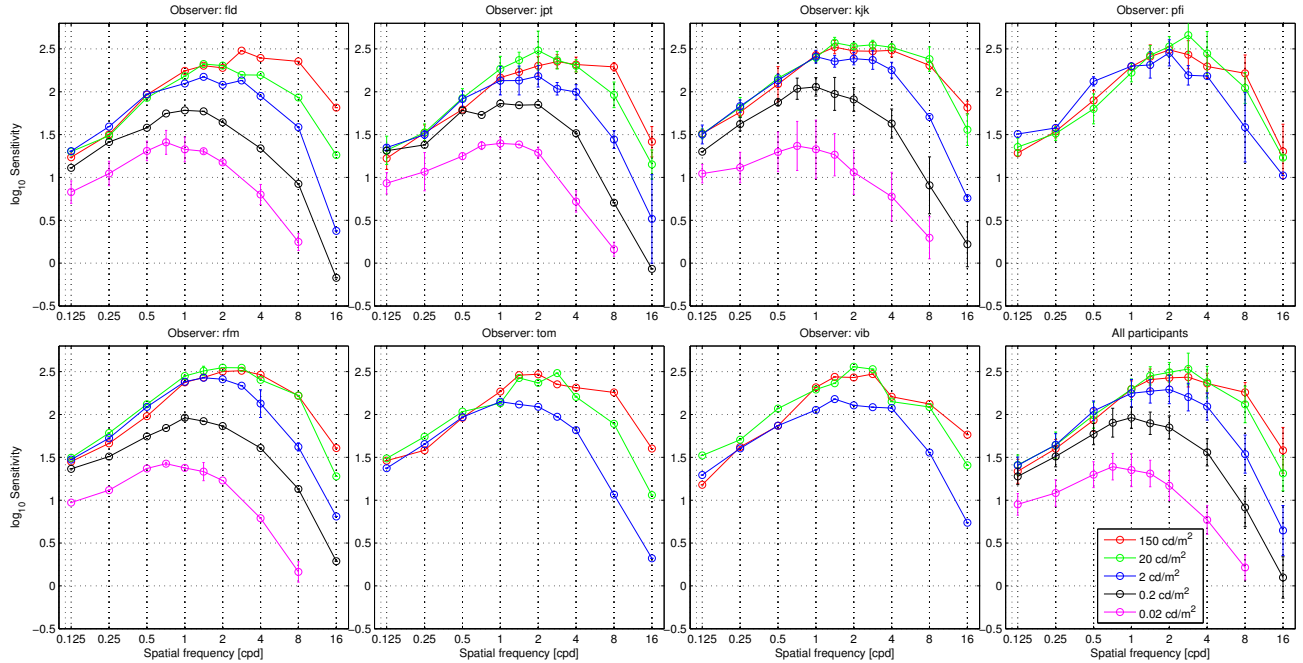


Figure 2. Measurements of the achromatic CSF (C1: black to white) for individual observers and averaged results across all observers (bottom-right plot). Different line colors denote different background luminance levels. If no error bar is present, only a single measurement (20-trials of the QUEST procedure) was made for that point. Otherwise, the error-bar denotes the standard deviation.

predefined to range from 0% to 100% visibility based on a prior knowledge derived from literature or a preliminary experiment. The adaptive procedures are based on the assumptions about the distribution of responses near the threshold and an actual shape of the psychometric function. In the adaptive procedure, many trials are repeated while varying the magnitude of the stimulus. The magnitude of a current trial is determined on the basis of the observer’s responses in previous trials. Based on the results of psychophysical experiments, these adaptive procedures are demonstrated to be more accurate and efficient than the constant-stimuli method<sup>20</sup> given the same number of trials. QUEST is an adaptive procedure. It has been widely used for estimating thresholds in psychology fields.<sup>21–24</sup> The QUEST algorithm assumes that the detection probability function of observer follows a Weibull distribution. In our experiment, the stimuli magnitude was the degree of the contrast. QUEST adaptively determines the degree of contrast for the next trial based on the observer’s response for the current comparison of the reference and test stimuli. Our custom experiment code used the QUEST implementation from Psychtoolbox (version 3), which is a Matlab toolbox for creating psychophysical experiments.<sup>25</sup>

## 4. RESULTS

### 4.1 Achromatic CSF

Figure 2 shows the results of the achromatic CSF (C1: black to white) measurements for individual observers and averaged results across all observers. The average observer data, plotted in the rightmost bottom plot, shows a typical band-pass characteristic with the peak frequency shifting from 2.8 cpd at 150 cd/m<sup>2</sup> to about 0.7 cpd at 0.02 cd/m<sup>2</sup>. As luminance decreases, so does sensitivity. However, the sensitivity does not drop with luminance for frequencies less than 1 cpd and the luminance range between 2 cd/m<sup>2</sup> and 150 cd/m<sup>2</sup>. There is little difference in sensitivities between 20 cd/m<sup>2</sup> and 150 cd/m<sup>2</sup>, which suggests that the Weber law is a good approximation of the visual system detection performance for higher luminance levels. The most unexpected observation is that the peak sensitivity for 20 cd/m<sup>2</sup> exceeds the peak for 150 cd/m<sup>2</sup> for the frequencies between 1.4 and 2.8 cpd, demonstrating that we can be more sensitive to lower luminance levels. Such a peak in sensitivity with increasing

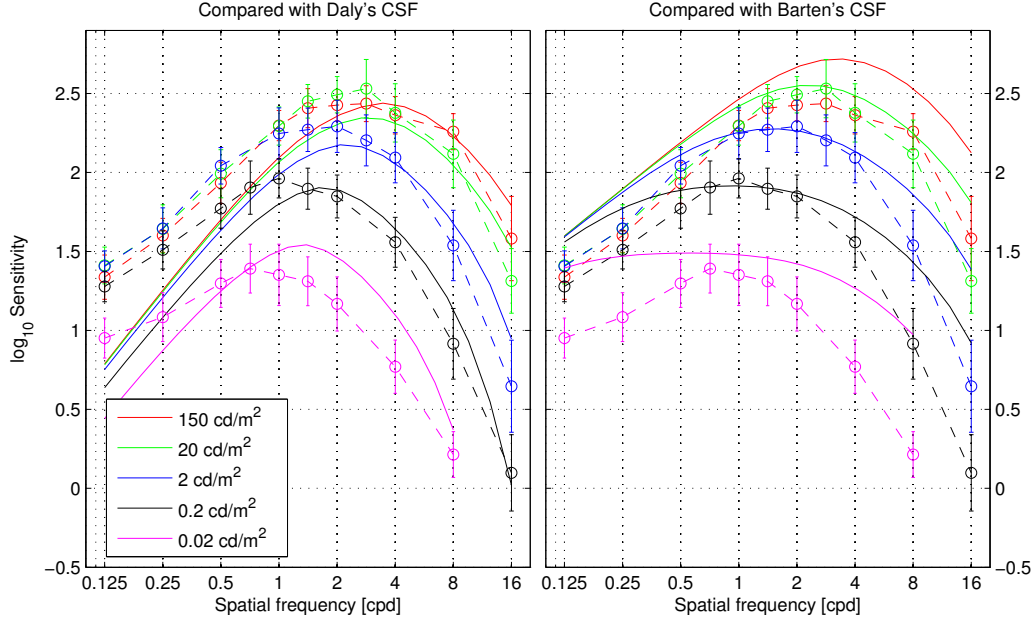


Figure 3. Comparison of our measurements of the achromatic CSF with two popular CSF models. The measurements are plotted as dashed lines with error band and the CSF models with solid lines.

luminance was also reported by Peli et al. [26, fig. 2] for 1 cpd and Van Nes and Bouman [27, figs. 5 and 6] at 4 cpd. However, no explanation for this effect was given.

The plots for individual observers show that the measurements are relatively consistent across observers, in particular at 20 cd/m<sup>2</sup> and 150 cd/m<sup>2</sup> background luminance. However, they tend to vary more in the mesopic range (for 0.2 cd/m<sup>2</sup> and 2 cd/m<sup>2</sup>) where both cones and rods contribute to detection. For example, the peak sensitivity at 2 cd/m<sup>2</sup> is at 1.4 for observers *rfm* and *kjk* but at 1.2 for other observers. The similar effect can be also observed at 0.2 cd/m<sup>2</sup> where the sensitivity for observers *rfm* and *kjk* is higher than for *fld* and *jpt*. This could be explained by the fact that the observers *rfm* and *kjk* were both experienced and completed similar experiments before. The observer *kjk* completed the experiment several times to estimate intra-observer variation. The error bars are the largest at the lower luminance levels, suggesting that the lower luminance levels may result in a lower slope of the psychometric function. The observers also reported that completing the 4AFC task was the most difficult at the lowest luminance levels.

The shape of the CSF curves varies from very smooth and regular for the observer *rfm*, to much more irregular for other observers. Some irregularities in the CSF shape could be explained by the measurement error and less experience with this type of experiment. But interestingly, such irregular shapes with multiple or strong peaks could be also observed for observers *jpt* and *kjk*, who completed many measurements and were relatively experienced. The curves for the *kjk* show two separate peaks separately at 2 cd/m<sup>2</sup> and at 20 cd/m<sup>2</sup>. We speculate that this can be evidence of the frequency-selective visual channels, proposed in many visual models.<sup>28</sup> The data for *jpt* shows a pronounced peak for 20 cd/m<sup>2</sup> data, significantly exceeding the sensitivity for high luminance levels (150 cd/m<sup>2</sup>). The effect is also visible for the average observer data. This could suggest that at least for some part of the population and for the frequencies around 2 cpd, the sensitivity peaks at the luminance levels close to 20 cd/m<sup>2</sup>, instead of steadily increasing with luminance as commonly assumed in most visual models.

## 4.2 Comparison with achromatic CSF models

Figure 3 compares our results with two popular CSF models: Barten's<sup>6</sup> and Daly's.<sup>8</sup> Parameters of both models were selected to match the stimuli used in our experiments as closely as possible. It is important to note that both models do not account for the temporal aspects of the CSF.

Daly’s CSF is plotted in the left plot of Figure 3 as the family of the band-pass contrast sensitivity functions. As the background luminance decreases, the sensitivity drops and the peak shifts towards lower frequencies, consistently with our results. However, Daly’s model also predicts much stronger drops in sensitivities for low frequencies, and much stronger shift in the peaks and lower sensitivity for  $0.02\text{ cd/m}^2$ . The differences are significant and we did not find a way to compensate for them by varying the parameters of the model.

The default set of parameters was used to plot Barten’s CSF model [6, p. 39] on the right of Figure 3. The model matches our data well for low frequencies. But the drop of sensitivity for high frequencies is smaller than in the case of our data. Barten’s model also predicts flattening of the CSF with lower luminance levels, which results in much less pronounced peak of the sensitivity at low luminance. We could not observe this behavior in our data. The predicted sensitivities for lower luminance levels are also much lower than found in the experiments. This is most likely because Barten’s model is valid for the photopic luminance range only and it was not meant to predict sensitivity for the luminance as low  $0.2$  or  $0.02\text{ cd/m}^2$ . The discrepancies of this model in the scotopic range are also reported in [6, p. 45,51].

The results show significant differences between both CSF models and our measured data. The differences do not necessarily indicate problems with the models, but rather that the data used for fitting these models was most likely measured for different stimuli than the one used in our experiments. For example, in our experiment the size of the stimuli was kept constant regardless of the frequency. This resulted in a larger number of displayed sine-wave cycles for higher frequencies. But it is known that the number of cycles has a significant effect on detection, especially for low frequencies.<sup>29</sup> Some CSF measurements kept the number of cycles constant and varied size, which could result in very different sensitivity results. Another significant difference was that the presentation time was not limited and the stimuli were not modulated over time in our measurement (0-Hz temporal frequency), while the majority of CSF measurements are performed for temporarily modulated stimuli. The most important observation from these differences is that the shape of CSF depends on a much larger number of parameters than spatial frequency and luminance and this fact must be considered when selecting a CSF model for a particular application. For example, the CSF meant for temporarily flickering Gabor patches may not be the most appropriate for predicting visibility thresholds in static images.

### 4.3 Chromatic CSF

The measurements of the chromatic CSF averaged over all observers are shown in Figure 4. The plots for the red-to-green (C2) and yellow-green-to-violet (C3) color axes show the low-pass characteristic of the chromatic mechanism, also reported in other studies. However, band pass shapes are weakly shown for the photopic range (i.e.,  $40\text{ cd/m}^2$  and  $200\text{ cd/m}^2$ ) for both C2 and C3. Such a moderate drop at low frequencies could be also observed in the measurements of Granger and Heurtley [10, fig. 2], even though they used flicker photometry to ensure isoluminance. The drop of sensitivity with increasing frequencies is moderate compared to the drop of sensitivity with luminance. The sensitivities at  $40\text{ cd/m}^2$  and  $200\text{ cd/m}^2$  are almost identical, similarly as for the achromatic CSF. In contrast to achromatic CSF, there is little change in the shape of the CSF with decreasing luminance.

The dark-green to light-pink (C6) and dark-yellow to light-blue (C7) color axes are the mixture of chromatic and achromatic CSFs. The sensitivity curves show the predominantly low-pass characteristic of the chromatic mechanism, but also the shift of the sensitivity towards lower frequencies, which is typical for achromatic CSF.

Figures 5 to 8 show the results of chromatic CSF measurements for individual observers and each color axis separately. Overall, the measurements are relatively consistent across observers, but there are also significant differences. For some observers the CSF is low-pass (e.g. C2,  $200\text{ cd/m}^2$ , rfm and ksw), and for some it is band-pass (e.g. C2,  $200\text{ cd/m}^2$ , kjk and rwn). This is most likely due to the fact that we did not tune the color axes individually for each observer to produce isoluminant stimuli for C2 and C3. Such isoluminant axes can be found using the flicker photometry method,<sup>11</sup> in which the observers adjust the axis until the flicker at certain frequency is the smallest. Moreover, the isoluminance is also changing with luminance level. As luminance decreases, the rod vision starts to dominate detection. Since rod spectral sensitivity differ from cones, the isoluminance color planes also differs between photopic and scotopic luminance levels. Therefore, even though color axis C2 and C3 were selected to produce isoluminant colors in terms of photopic vision and CIE standard observer, the stimuli contained a small amount of luminance contrast.



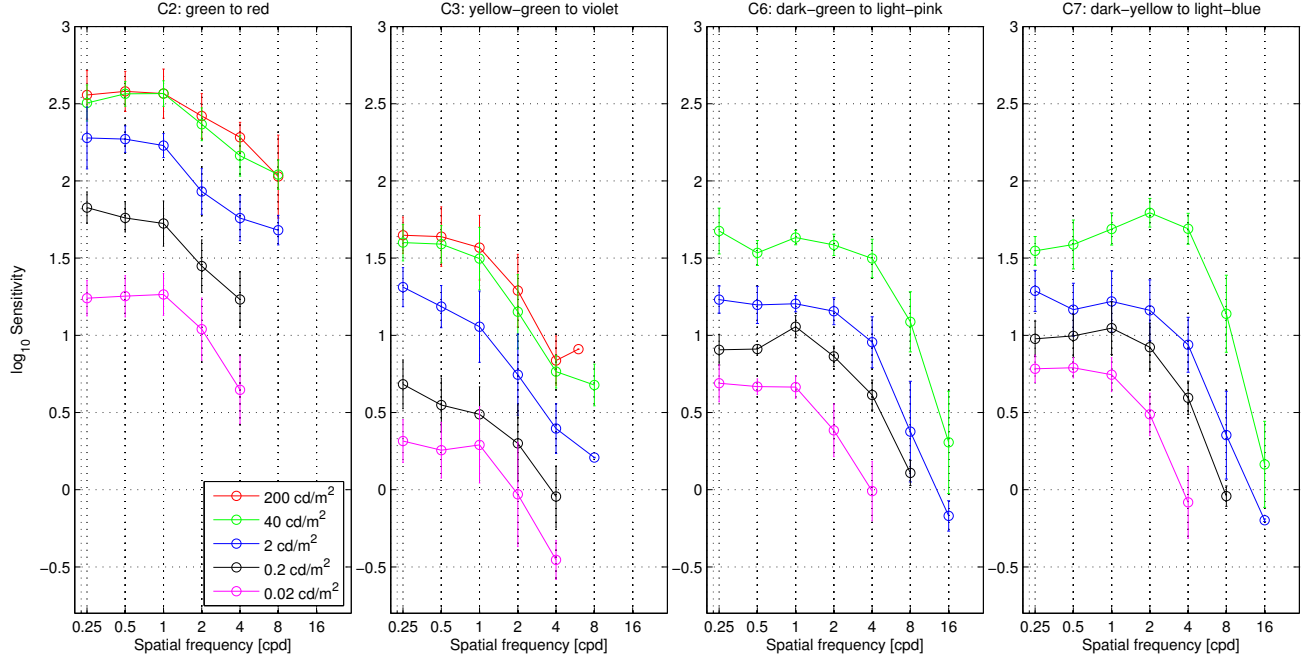


Figure 4. Measurements for chromatic CSF (C2 and C3) and mixed chromatic and achromatic CSF (C6 and C7) — averaged over all observers.

#### 4.4 Comparison with chromatic CSF models

Figure 9-left compares our results with ColorFest’s chromatic CSF models (model GSMA, fit for all observers). The data is plotted for the same luminance level as used in ColorFest measurements —  $40 \text{ cd/m}^2$ . The ColorFest model predicts higher sensitivity loss for high frequencies than found in our measurements. Also, the sensitivity for C2 was found to be lower in our measurements. The latter difference could be explained by different white point of the background used in our experiments. When the white point from the ColorFest experiments is used for contrast calculation, the C3 sensitivity better matches the one predicted by the model.

The right-side of Figure 9 compares our results with the CSF used in the sCIELab — the spatial extension of the CIELab color difference metric.<sup>16</sup> The functions were plotted after the Fourier transformation of the original formula defined in the spatial domain [16, sec. 4] and using the parameters from the MATLAB implementation of the metric. These parameters differ from the ones reported in the paper because they are adjusted to ensure that the CSF components sum to 1 (refer to the paper for details<sup>16</sup>). sCIELab CSF functions indicate stronger drop of sensitivity for C2 and higher cut-off frequency for C3. However, it must be also noted that the color axis and luminance levels used in the sCIELab metric do not need to be the same as the ones used in our experiments.

The most likely explanation for the lower drop of sensitivity at high frequencies in our data is the intrusion of luminance signal in the stimuli. Unless the color axis is tuned separately for each individual observer and luminance level to ensure isoluminance, the stimuli will be partially detected by the achromatic mechanism. However, tuning color axis for individuals is certainly impractical for most visual models. Therefore, it could be argued that modelling chromatic mechanism with some amount of achromatic intrusion and thus lower drop at high frequencies is likely to better predict the performance of an average observer.

## 5. CONCLUSION

To capture the effect of luminance on contrast detection of both chromatic and achromatic patterns, new CSF measurements were conducted for a range of luminance levels from  $0.02 \text{ cd/m}^2$  to  $200 \text{ cd/m}^2$ . The goal was to capture a possibly broad range of frequencies and luminance levels under the same viewing conditions. The focus of this study was on detection under natural viewing conditions, without restricting fixation point, controlling

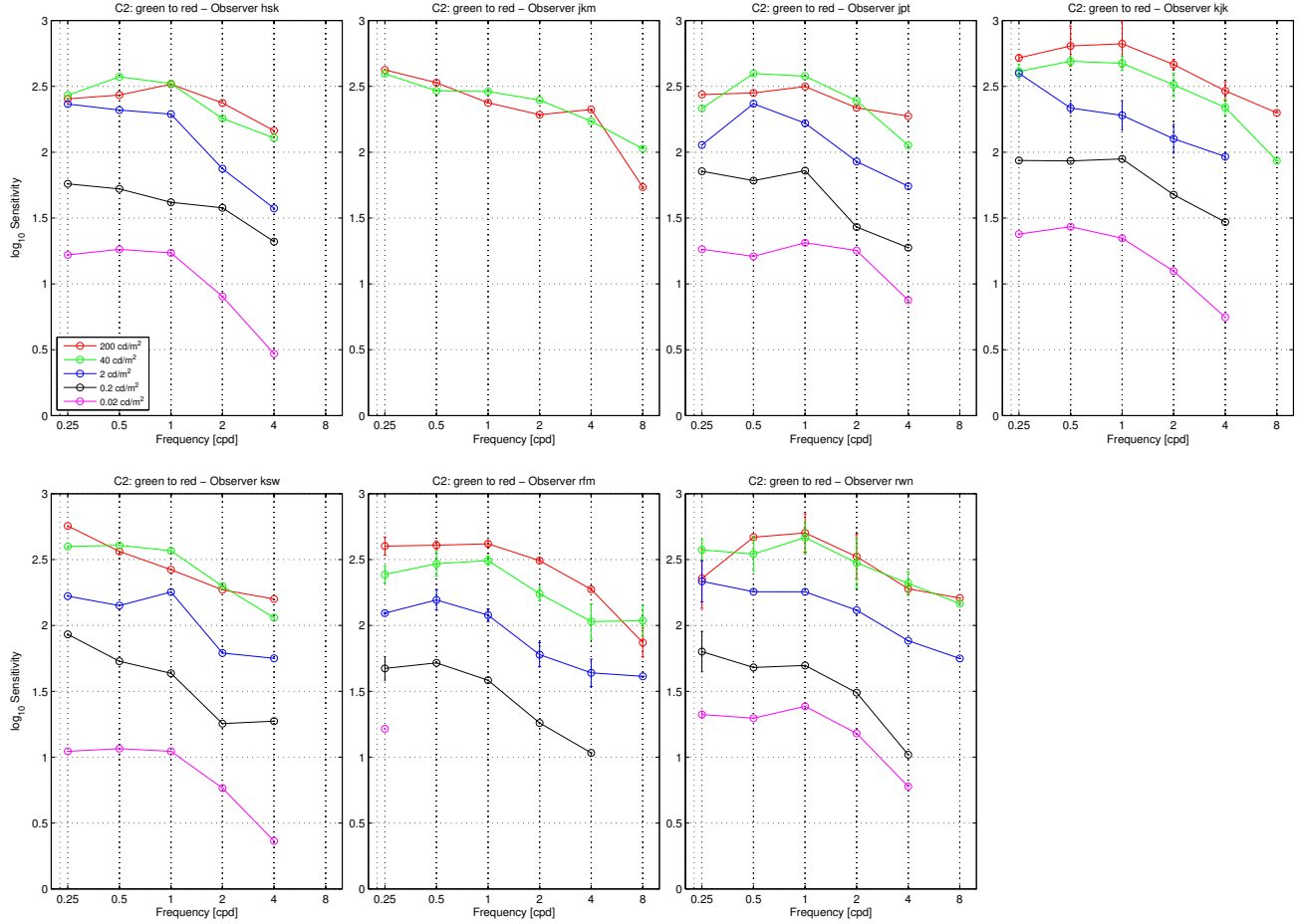


Figure 5. Results for C2 (green to red)

pupil, or introducing temporal modulation. We believe that such conditions are more relevant if the data is to be used for general visual models meant to predict performance for static images.

We found significant differences when our data was compared to popular CSF models of Barten and Daly. We observed higher sensitivity drop for higher frequencies and significant differences in sensitivities as compared to these models in the luminance range between 0.02 and 2  $\text{cd}/\text{m}^2$ . We attribute these differences to the variations in viewing conditions and stimuli.

Our measurements for chromatic CSF show a significant drop in sensitivity with luminance, but little change in the shape of the CSF. The drop of sensitivity at high frequencies is significantly weaker than reported in other studies and assumed in most chromatic CSF models.

In the future work, we wish to measure both chromatic and achromatic CSF at higher luminance levels. Such measurements will most probably involve a high-dynamic-range display. We also wish to measure the chromatic CSF for higher frequencies to clarify discrepancies between our measurements and popular chromatic CSF models. Finally, we plan to fit an analytical model that could be used to interpolate our data. Such model was derived for our achromatic data,<sup>5</sup> but a more general model that could explain both chromatic and achromatic data is needed.

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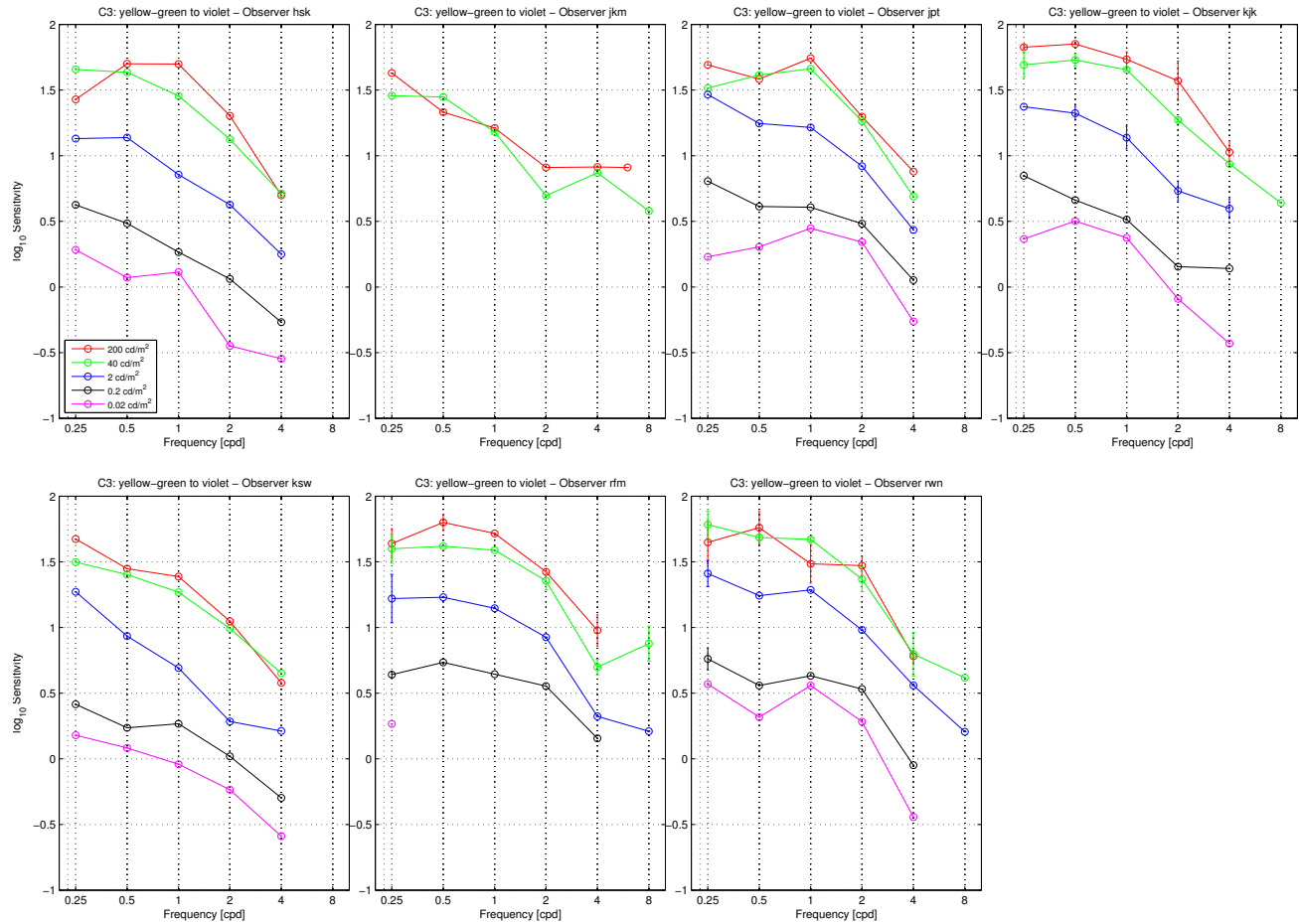


Figure 6. Results for C3 (yellow-green to violet)

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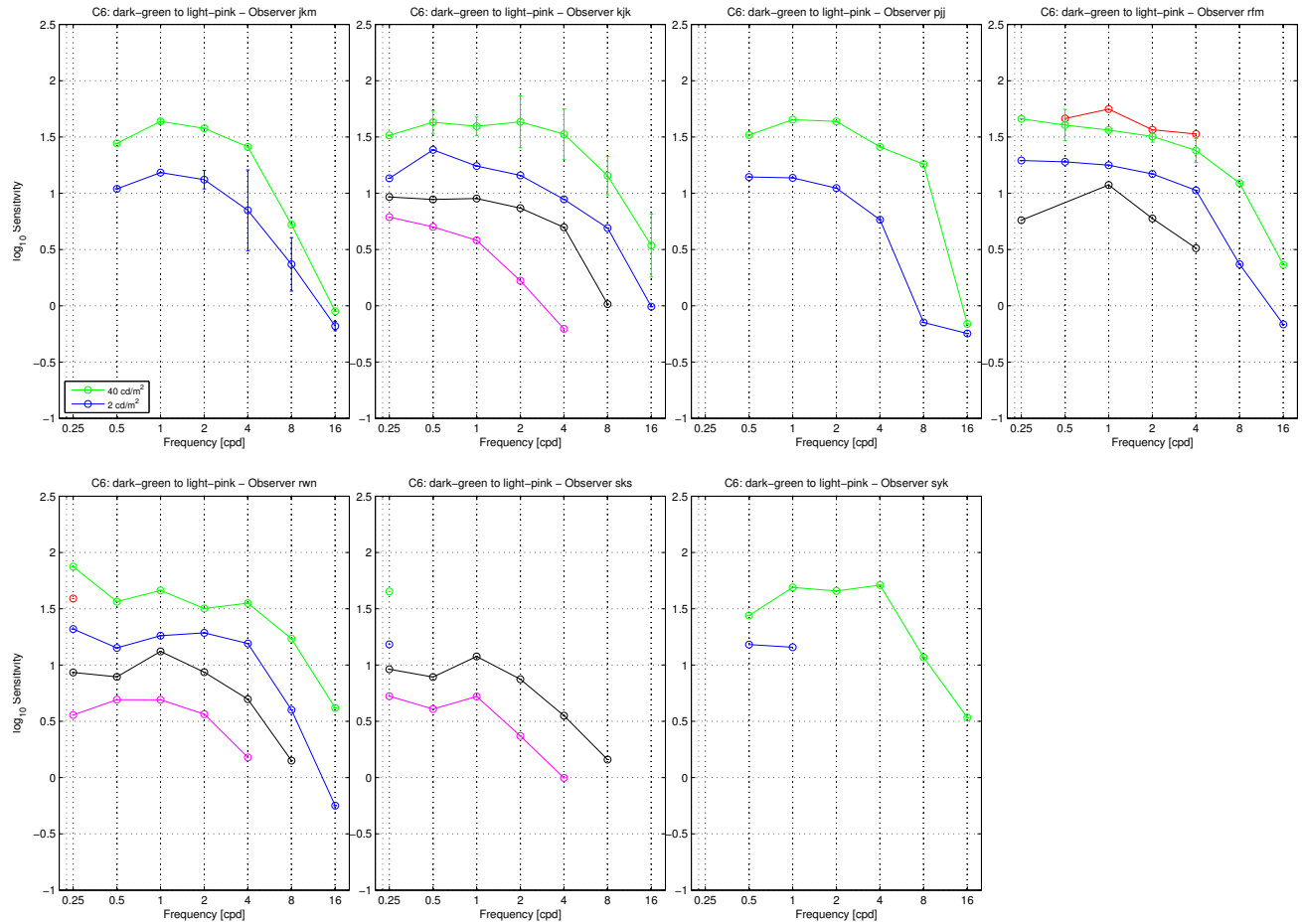


Figure 7. Results for C6 (dark-green to light-pink)

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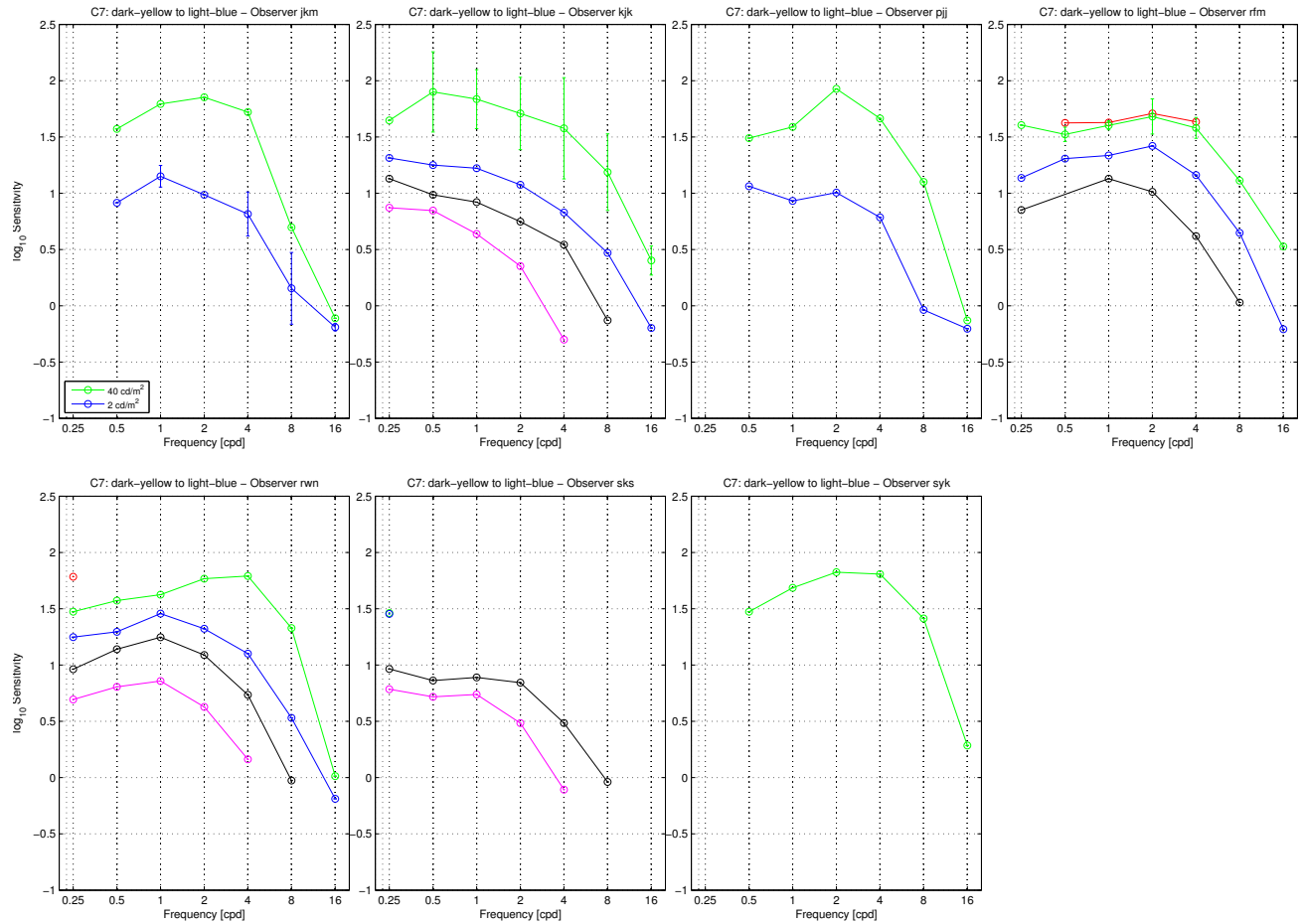


Figure 8. Results for C7 (dark-yellow to light-blue)

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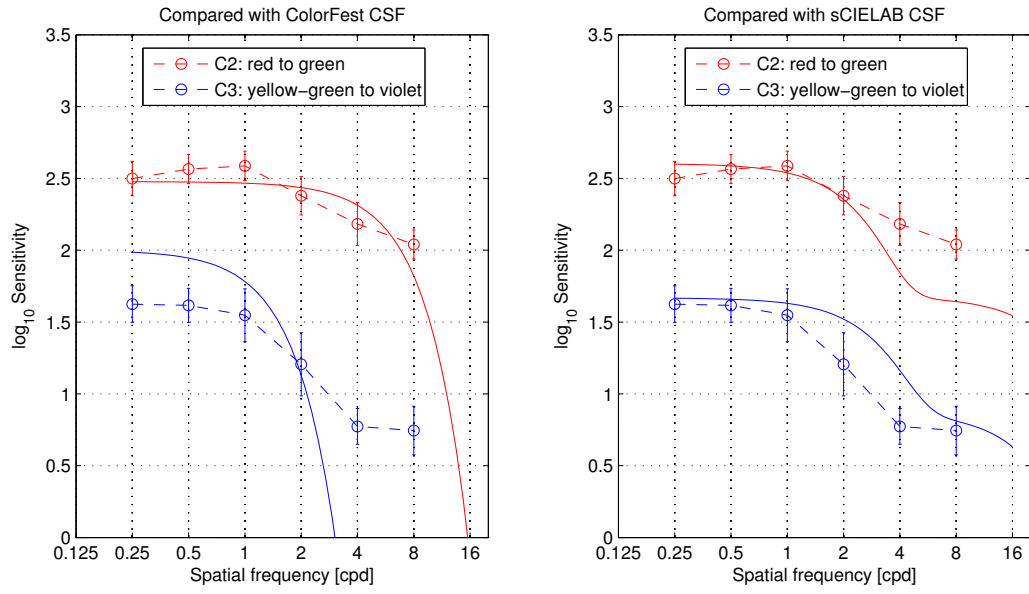


Figure 9. Comparison of our measurements of the chromatic CSFs at 40 cd/m<sup>2</sup> background luminance with ColorFest CSF model (left) and with the CSF used in the sCIELab metric (right). Our measurements are plotted as dashed lines with error bars while the models are plotted with solid lines.

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