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Modelling Contrast Sensitivity for Chromatic Temporal Modulations

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Abstract

The temporal contrast sensitivity to isoluminant chromatic flicker was measured for three observers using the method of adjustment. The isoluminant stimuli were created for each observer individually, based on a technique similar to heterochromatic flicker photometry. The chromatic flicker stimuli were sinusoidal modulations, defined in the CIE 1976 UCS (u',v') chromaticity diagram. The chromaticity varied around a base color along a certain modulation direction with a certain amplitude at a certain frequency. Nine base colors, four modulation directions and seven frequencies were used, resulting in thirty-six temporal contrast sensitivity curves per observer. An exponential model was fitted to the resulting contrast sensitivity expressed as 1/Δ(u', v'), 1/ΔLMS and 1/Δlms. The model resulted in an average R^2 value higher than 0.93 for the three different measures of contrast sensitivity. The two parameters of the model (i.e. the slope β_1 and intercept β_0) were found to significantly depend on the base color and direction of the chromatic modulation. This means that Δ(u', v'), ΔLMS and Δlms are not suitable measures to predict the sensitivity to temporal chromatic modulations in different locations of the color space.

Introduction

The development of light emitting diodes (LEDs) technology has enabled inexpensive ways to easily create dynamic colored light. However, current knowledge on human perception of dynamic colored light is limited and still insufficient to provide guidelines for comfortable and attractive implementations. Some studies aiming at understanding the perception of dynamic light have concentrated on the perceived smoothness [1], the preference [2], and the perceived subtlety [3] of temporal color transitions. The limited number of studies show that existing spatial color spaces cannot be used to accurately predict these phenomena and that a temporally uniform color space is needed. The sensitivity to temporal modulations in luminance and chromaticity is a useful paradigm to collect data for building such a model.

The sensitivity of the human visual system to temporal modulations is known to depend on the modulation frequency. Above a certain critical fusion frequency (CFF), the modulation cannot be perceived independent of its magnitude. Below the CFF, the relationship between temporal frequency and sensitivity is called the Temporal Contrast Sensitivity Function (TCSF). TCSFs have been extensively studied in the past mainly for two purposes. First, in clinical vision science, for instance, to detect a variety of pathologies affecting the visual system [4], [5]. Second, to understand the underlying mechanisms of human vision [6] - [14].

In order to build a temporal color space a large amount of data has to be collected over the entire color space. Therefore, an efficient way of sampling the color space is required. As a first step, it would be beneficial to have a model describing the TCSFs with a small number of parameters, so we can use less temporal frequencies to subsequently study the TCSF in various locations of the color space. Researchers have found that the TCSF for luminance modulations is generally a band-pass function [15]. For chromatic modulations the TCSF is usually a low-pass function, where the sensitivity decreases with increasing frequency [16], [17]. However, some studies have found a small decrease in sensitivity also at low frequencies [18]. The TCSF has also been found to depend on the demographics (e.g., age) of the observers as well as stimulus features (e.g., stimulus size, retinal illuminance, characteristics of the surrounding) [8], [19].

Several models for TCSFs have been proposed. For instance, Dobkins et al. [17] used a double exponential function to fit the TCSFs for luminance and found that a single exponential function was sufficient to describe the TCSF for chromaticity. Other physiologically based models exist based on stimuli that activate only part of the visual system (e.g., the red-green opponency channel) [10]. Due to technical limitations at the time, most experiments on chromatic TCSFs have been carried out for limited color stimuli, usually red-green chromatic flicker. In this study, we investigate if the relationship between chromatic contrast sensitivity and temporal frequency can be described by the same exponential function for a wide range of chromatic flicker stimuli. In particular, we vary the base colors (i.e. the mean color of the chromatic modulation) and the modulation direction in the 1976 UCS (u',v') chromaticity diagram.

Method

In this study, the detection threshold of chromatic flicker was measured for 9 base colors, 4 directions of chromaticity change and 7 temporal frequencies, using a full-factorial within-subject design with 3 participants. Before the main experiment, a preparation experiment was performed to determine the luminance ratios between two alternating colored stimuli that minimizes the visibility of luminance flicker for a given participant using a method similar to heterochromatic flicker photometry (HFP). The luminance ratios were determined for the 36 color pairs used in the main experiment with a chromaticity difference of 0.05 Δ(u',v') at a flicker frequency of 25 Hz. The individual luminance ratios were used to make the isoluminant chromatic flicker stimuli of the main experiment.

Experimental Setup

A specially designed LED system, with 36 Cree XP-E LEDs arranged in a square panel (12 red, 8 green and 16 blue LEDs), was used. The system was calibrated with a spectrometer and shown to be reliable and stable over time. The LEDs were driven by means of pulse width modulation (PWM) at a driving frequency of 2 kHz and having 16-bit dimming. The PWM signals were generated by an Arduino Due microcontroller, which was connected to a lab computer. The drivers of the LEDs accepted RGB values, in the device dependent color space of the LEDs. The target stimuli were defined in CIE 1976 UCS (u',v') and transformed via XYZ to the RGB values of the LEDs.

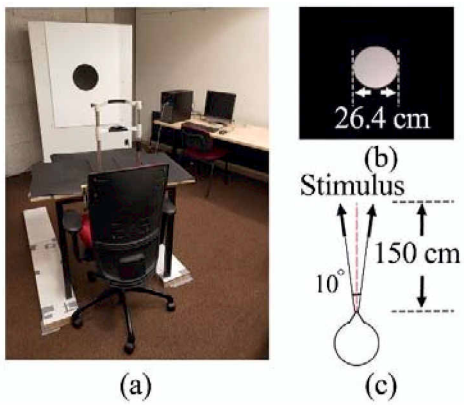

Figure 1. (a) Overview of the lab environment (b) Front view of the stimulus (c) Top view of the participant and stimulus.

The LED panel was placed in a box (height: 1.5 m, depth: 0.8 m, width: 1.5 m) with a circular opening of 26.4 cm in diameter (see ***Figure 1***). Participants were seated at a predefined position of 1.5 m from the front of the box, which resulted in a stimulus covering a visual angle of 10-degrees. Since we are interested in using the data for realistic lighting applications, a 10-degrees field was preferred over 2-degrees. Participants could only see the stimuli from this circular opening. The inner surfaces of the box were smooth and colored natural white. The LEDs were mounted in such a way that the visible light field was quite uniform (i.e., the luminance deviated by a maximum of 3.3% at the stimuli luminance level of 37.5 cd/m^2, while the chromaticity deviated by a maximum $\Delta(u',v') = 0.0013$). The inner edges of the box and the luminaries were not visible.

To avoid head movements of the participants, a chinrest was used. Additionally, a standard keyboard was provided as an input device for the participants.

Stimuli

The stimuli consisted of light sinusoidally modulated in time. The chromaticity of the light varied around a base color in a predefined direction specified in the CIE 1976 UCS (u',v') chromaticity diagram. Depending on the individual luminance ratios, the luminance of the light varied at the same temporal frequency as the chromaticity to make the stimulus isoluminant for each participant.

Nine base colors (BC_1 to BC_9) were selected (see ***Figure 2***). The chromaticities of BC_1, BC_2 and BC_3 were close to the green, blue and red LED, respectively. BC_4, BC_5 and BC_6 were the middle points between BC_1 and BC_3, BC_1 and BC_2, BC_2 and BC_3 respectively, while BC_7 was located in the center of the gamut. During the experiment we discovered that it was impossible to make the entire 10-degree visual field non-flickering for BC_2 and BC_3 at the selected frequencies and amplitudes. Instead, the colors could be fused either for the center of the field or at the outer edge, but not for the entire field at the same time. Therefore, two other base colors (BC_8 and BC_9), which were less saturated versions of BC_2 and BC_3, were added. The chromaticity coordinates of the base colors are shown in **Table 1**.

Four modulation directions were chosen, namely 0° (i.e. parallel to the direction of the u' axis), 45°, 90° (i.e. parallel to the v' axis) and 135° (as shown in ***Figure 2***). The amplitude of the modulation varied between 0.00004 $\Delta(u',v')$ and 0.05 $\Delta(u',v')$. The luminance ratio of the two extreme colors of each sinusoidal modulation was based on the individual isoluminance, as determined by the preparation experiment. The average luminance of the stimulus was 35 cd/m^2. The temporal frequency of the light modulation was 2, 4, 8, 10, 15, 20 or 25 Hz. **Table 1** shows the variables of the 252 (i.e., 9 base colors × 4 directions × 7 frequencies) conditions.

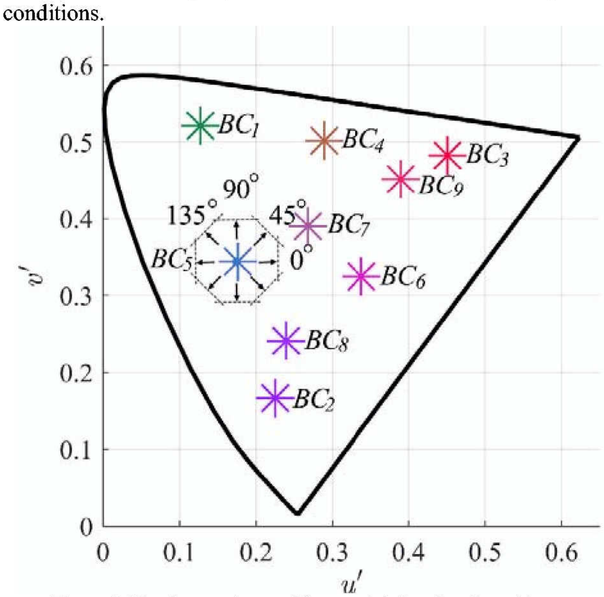

Figure 2. Nine base colors and four modulation directions (shown around BC_5) in the CIE 1976 UCS (u',v') chromaticity diagram.

Table 1. The stimulus variables of the 252 conditions

BC	u'	v'	Modulation Direction	Frequency
1	0.1273	0.5213	0° 45° 90° 135°	2 Hz 4 Hz 8 Hz 10 Hz 15 Hz 20 Hz 25 Hz
2	0.2251	0.1663		
3	0.4509	0.4826		
4	0.2891	0.5019		
5	0.1762	0.3438		
6	0.3380	0.3245		
7	0.2678	0.3901		
8	0.2393	0.2409		
9	0.3899	0.4517		

Participants

Three participants performed the experiment (**AM**, female, 25 years; **MB**, male, 27 years; **XK**, male, 27 years). The participants received elaborate training and two of them had previous experience with chromatic flicker experiments. All participants had normal color vision, as measured with the Ishihara test for color deficiency and one of them was wearing glasses for corrected visual acuity. None of them were susceptible to migraine and/or epileptic seizures.

Procedure

The experimental procedure was approved by the Daily Board of the Human-Technology Interaction group, Eindhoven University of Technology for ethical considerations. The main experiment was divided into different sessions on different days since it was too fatiguing for the participant to measure all conditions at once. The task of the experiment was explained both in text and orally by the experimenter. Before the start of the first session, participants were asked to sign an informed consent form, in which they were informed on their voluntary participation. Then an Ishihara color deficiency test was performed, followed by the collection of demographic information.

In each session, participants were instructed to sit down in the chair at the predefined position. They could adjust the chinrest and the height of the chair to a comfortable position before the experiment started. The method of adjustment was used to find the detection threshold of chromatic flicker. In a previous unpublished study, this method was shown to be both accurate and efficient to measure chromatic flicker thresholds. In order to correct for a possible error of anticipation, the adjustment was performed once with a relatively high starting amplitude and once with a low starting amplitude. In addition, participants were trained to use a consistent decision criterion to minimize the variance within participants [20].

Each trial started with a beep sound, indicating the participant could start with the adjustment. The first stimulus of the trial had either a modulation amplitude of 0.05 $\Delta(u',v')$, for which flicker was clearly visible, or an amplitude of 0.0004 $\Delta(u',v')$, which appeared to be static. Participants were instructed to look at a fixation point in the center of the circular opening of the apparatus and to find the smallest amplitude at which the flicker was just visible, by increasing or decreasing the amplitude of the chromatic modulation. They could use the up and down arrow keys of a keyboard to increase or decrease the modulation amplitude with a large factor, while the left arrow and right arrow keys could be used to change the modulation amplitude with a small factor. The modulation amplitude was changed by a factor F:

$$F = \frac{A_{n+1}}{A_n} = 1.1^{\pm\alpha} \quad (1)$$

where A_n refers to the amplitude of the current stimulus, A_{n+1} refers to the amplitude of the next stimulus, and α equals 2 for the small factor, while α equals 5 for the large factor. When participants reached the lowest or highest amplitude of the stimulus range, they heard a warning signal indicating that they could not go lower or higher, respectively. When participants were satisfied with the stimulus that represented their detection threshold, they were instructed to look at the final stimulus for one or two seconds before deciding to really end the adjustment procedure. After pressing the *Enter* key, the next trial was presented.

The first session was a training session, which aimed to get the participants familiar with the method of adjustment and the experimental task. Participants were instructed to find a useful strategy and to stick to that strategy during the rest of the experiment. Subsequently, each base color was presented in a separate session, and the order of the base colors was the same for all participants (from BC_1 to BC_9). At the beginning of a session, a static adaptation stimulus with the chromaticity of the base color and a luminance of 37.5 cd/m^2 was presented for two minutes. Next, the conditions were presented in a random order. For each base color, there were 56 conditions (i.e., 7 frequencies × 4 directions × 2 starting amplitudes). Each session took about 30 minutes, and the experiment took 4.5 hours in total (without the preparation experiment and the training session).

After each session, participants were asked to write down some notes regarding their experience with the experiment. During the experiment, the chromaticity values of all stimuli that were shown were stored together with a time log. These data were used to look at the strategy of the participant and for further analyses.

Analyses and Results

The experiment resulted in 504 detection thresholds (i.e. 252 conditions × 2 starting amplitudes) expressed in CIE 1976 UCS $\Delta(u',v')$ for each participant. The thresholds can be plotted as a function of frequency for each base color, modulation direction and participant. ***Figure 3*** shows an example of the data of participant **MB** at BC_1 for the four modulation directions. From ***Figure 3,*** we can see that the threshold increases as the frequency increases. There also seems to be an effect of modulation direction, which is most visible at 25 Hz. Moreover, the thresholds of the two starting amplitudes are quite consistent with each other.

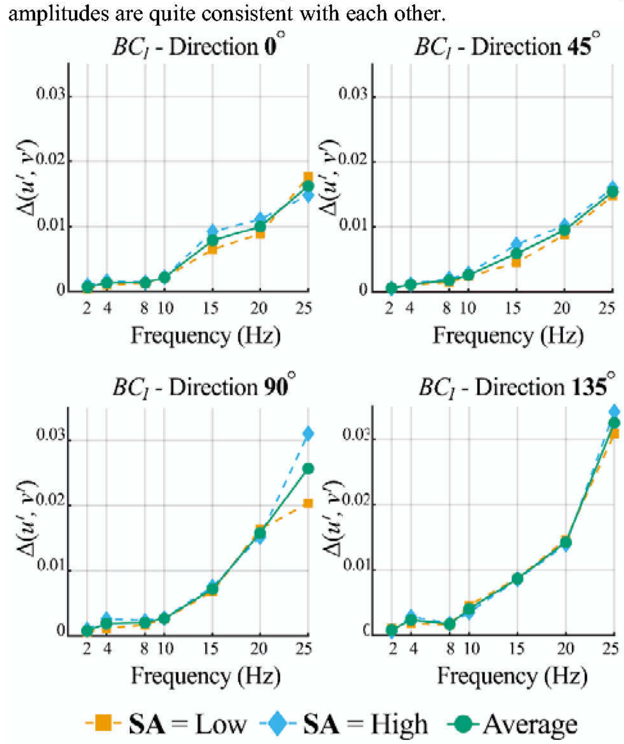

Figure 3. The chromatic flicker threshold in $\Delta(u',v')$ as a function of modulation frequency for BC_1 for the four modulation directions for participant **MB**. The two dashed lines show the thresholds for the two starting amplitudes (SA) and the solid line represents their average.

These conclusions were confirmed by a linear mixed model analysis (LMM) with *Detection Threshold* as dependent variable and *Base Color*, *Modulation Direction*, *Frequency* and *Starting Amplitude* as fixed independent variables and with a random intercept for *Participant*. The analysis revealed a significant main effect of *Base Color* ($F(8,1509)=36.854$, $p<0.001$), *Modulation Direction* ($F(3,1509)=126.435$, $p<0.001$), *Frequency* ($F(6,1509)=892.323$, $p<0.001$) and *Starting Amplitude* ($F(1,1509)=5.234$, $p=0.022$). A low starting amplitude resulted in a slightly lower detection threshold compared to a high starting amplitude (MD = 0.001, p = 0.022), which was also found in the unpublished study. The detection thresholds were averaged over the two starting amplitudes for further analysis.

Modelling of TCSFs

In order to model the TCSF for chromatic modulations, we expressed the data in terms of *contrast sensitivity* (i.e. the reciprocal of the detection threshold expressed as chromatic contrast). Three measures of contrast were used: $\Delta(u', v')$, ΔLMS (using Equation (2)) and Δlms (using Equation (3)).

$$\Delta LMS = \sqrt{(\Delta L)^2 + (\Delta M)^2 + (\Delta S)^2} \quad (2)$$

$$\Delta lms = \sqrt{(\Delta l)^2 + (\Delta m)^2 + (\Delta s)^2} \quad (3)$$

where ΔL, ΔM, ΔS are the differences between the L-, M-, and S-cone responses of the two extreme colors of the chromatic flicker stimulus at threshold modulation, which are calculated using the cone fundamentals of Stockman and Sharpe [21], and Δl, Δm, Δs are the differences between the L-, M- and S-cone responses normalized with respect to the sum of the cone responses.

For each contrast measure, the contrast sensitivity was plotted as a function of frequency, resulting in 36 (i.e. 9 base colors × 4 directions) TCSFs per participant. These TCSFs were fitted with:

$$S = \frac{1}{C} = e^{\beta_1 f + \beta_0} \quad (4.1)$$

where S is the contrast sensitivity, C the detection threshold and f the temporal frequency. Equation (4.1) can be rewritten as:

$$lnS = \beta_1 f + \beta_0 \quad (4.2)$$

with β_1 being the slope and β_0 the intercept of the function.

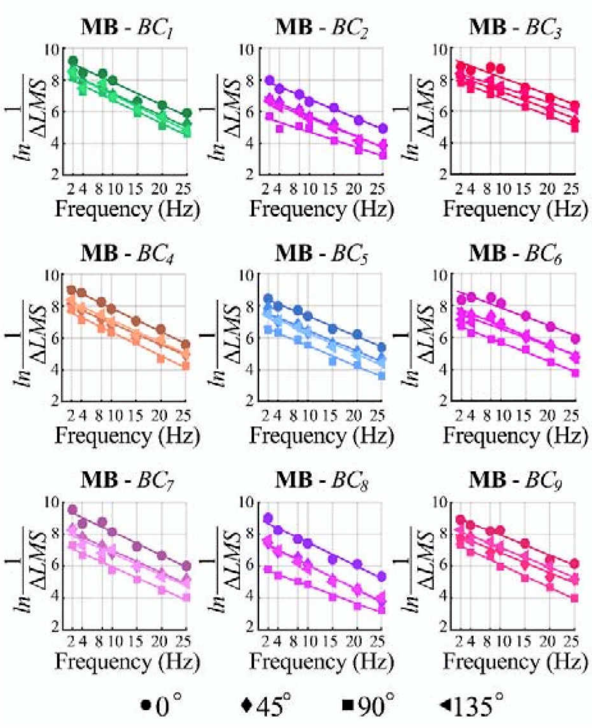

Figure 4. The contrast sensitivity as a function of frequency for all base colors (BC_1 to BC_9) and the four directions (0°, 45°, 90° and 135°) for participant **MB**. The straight lines represent the fitted functions according to Equation (4.2).

For all three contrast measures, the average goodness-of-fit expressed in R^2 was higher than 0.93 and they were all very similar to each other (i.e., the average R^2 differed by a maximum of 0.0002). For further analysis, we chose ΔLMS as our contrast measure. The R^2 averaged over all conditions was 0.86, 0.97 and 0.96 for participant **AM**, **MB and XK**, respectively. As an example, ***Figure 4*** shows the data and the fitted functions for all the TCSFs of participant **MB.**

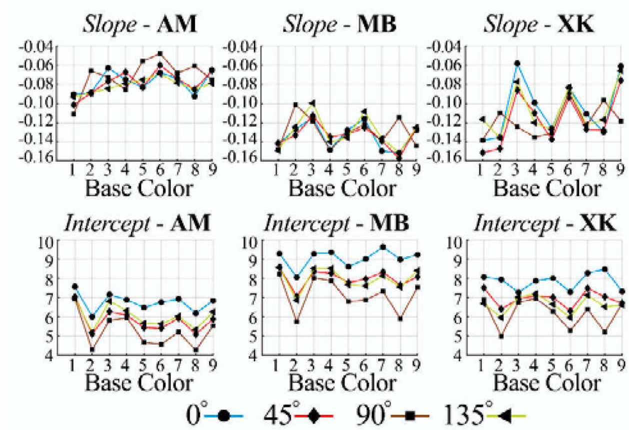

Figure 5. The slopes and intercepts of the fits of all conditions for the three participants.

Figure 5 gives the slopes (β_1 from Equation (4.2)) and intercepts (β_0 from Equation (4.2)) of the fits for the three participants. The figure shows that there are differences between the participants in the absolute values of the slope and intercept of the TCSF, but also in the effect of base colors and modulation direction, especially for the slope. In order to test the overall effect of base color and modulation direction, two separate linear mixed model (LMM) analyses were performed: (1) with *Slope* (β_1) as the dependent variable and (2) with *Intercept* (β_0) as the dependent variable. In both analyses, *Base Color* and *Modulation Direction* were the fixed independent variables. We also included the interaction term between these two variables and a random intercept for *Participant*. The resulting p-values were obtained from a Type III sum of squares. Post-hoc analyses with Bonferroni correction were performed for the significant effects.

For the *Slope*, the LMM analysis showed a significant effect of *Base Color* ($F(8,105)=16.375$, $p<0.001$). BC_1 had the lowest slope, BC_3, BC_6 and BC_9 had the highest slope and the slopes of the other base colors were in between and not significantly different from each other. There was also a significant interaction effect between *Base Color* and *Modulation Direction* ($F(24,105)=2.586$, $p<0.001$). However, no significant main effect was found for *Modulation Direction* ($F(3,105)=0.762$, $p=0.518$). The effect of *Modulation Direction* on *Slope* was different for different base colors, for example, BC_3 had the highest value of the slope at Direction 0°, while BC_2 had the highest value at Direction 90°.

For the *Intercept*, the effect of *Base Color* ($F(8,105)=41.949$, $p<0.001$), *Modulation Direction* ($F(3,105)=179.595$, $p<0.001$) and the interaction between *Base Color* and *Modulation Direction* ($F(24,105)=3.249$, $p<0.001$) were significant. BC_2 had the lowest value of the intercept, which was significantly lower than all the other base colors, and BC_1, BC_3 and BC_4 had the highest intercept. We also found that the intercept was lowest for Direction 90° and highest for Direction 0°. The intercept of the other two directions was in between and not significantly different from each other. For all base colors, the trend of the *Intercept* over the four modulation directions was the same. Direction 0° always had the highest *Intercept*, followed by Direction 135°, Direction 45° and Direction 90°. However, the difference was not significant for all base colors.

Discussion

In this study, we measured the detection threshold of chromatic flicker and obtained TCSFs for nine base colors and four modulation directions for three participants. Instead of exploring inter-observer differences or modelling an average observer, we aimed at measuring and modelling individual observers. We found that the TCSF of all participants could be described by the same exponential model, the parameters of which changed from person to person. More research is needed to investigate if the model depends on demographic factors, such as the age of the observer.

The contrast sensitivity was defined as the reciprocal of ΔLMS, i.e. the difference between the LMS cone responses of the two extreme colors of the chromatic flicker stimulus at threshold modulation. The TCSFs were fitted with an exponential function (see Equation (4.1)). The model fitted the data very well, with R^2 values around 0.90. The two parameters of the model (i.e. the slope β_1 and intercept β_0) were found to be dependent on the base color and modulation direction. This means that the visibility of a chromatic temporal modulation at a given frequency does not only depend on the ΔLMS of the two (extreme) colors of the modulation, but also on the LMS values themselves. So, ΔLMS itself cannot be used to accurately predict the visibility of temporal changes in light.

The results indicate that the chromatic TCSF is a low-pass function, which is in line with other studies using isoluminant stimuli [22], [23]. Even though we did not directly measure the CFF, we can conclude that it must be higher than 25 Hz, since participants still could see flicker at some modulation amplitudes. The CFF probably depends on base color and modulation direction, as can be seen in ***Figure 4***.

In our experiment the average luminance of the chromatic flicker stimuli was fixed at 37.5 cd/m^2. However, retinal illuminance has been found to influence the chromatic TCSF [8], [19]. Therefore, it is important to explore the effect of luminance level in future work.

Since the contrast sensitivity for chromatic temporal modulations can accurately be described by a simple exponential model for a wide range of color stimuli, it is not necessary to use a large number of frequencies to determine the TCSF in a certain location of the color space. Instead, only a few frequencies are enough, which would greatly reduce the duration of the experiment. For future studies, we plan to measure the TCSF for more base colors, modulation directions and average luminance values in order to ultimately develop a representative temporal color model.

Conclusion

The contrast sensitivity for chromatic temporal modulations expressed in $1/\Delta LMS$ was found to be a good indicator to describe the relationship with frequency. An exponential model with two parameters (i.e. slope and intercept) described the TCSFs with very high accuracy (with an average R^2 higher than 0.93 for the three observers). The two parameters of the model were found to significantly depend on the base color and direction of the chromatic modulation.

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