EINDHOVEN UNIVERSITY OF TECHNOLOGY

HTI RESEARCH PROJECT

Measuring the Temporal Contrast Sensitivity Function for Isoluminant Chromatic Flicker Stimuli: An Extended Experimental Paradigm

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Abstract

The development of light emitting diodes (LEDs) technology has enabled inexpensive ways to create colored and dynamic light effects. However, current knowledge on human perception of dynamic colored light is still insufficient to provide guidelines for comfortable and attractive implementations. A uniform color space for dynamic light is needed for this goal, and chromatic flicker is a useful paradigm to study the sensitivity of human observers to color differences in the temporal domain. The ability to detect chromatic flicker depends on the temporal frequency (i.e. the temporal contrast sensitivity function, TCSF). Three experiments were carried out to measure TCSFs for isoluminant chromatic flicker stimuli at fifteen base colors, four modulation directions (in CIE 1976 UCS color space) and three frequencies. In Experiment 1, isoluminant settings, which were expressed as luminance ratios, for chromatic flicker were measured for 15 participants. The results showed inter-individual differences in luminance ratios and main effects of base color and modulation direction. In Experiment 2, TCSFs were measured (and modelled) for three participants using their individual luminance ratios for isoluminant stimuli. The results confirmed that TCSFs for chromatic flicker can be modelled with an exponential function. Besides, there were significant main effects of participant, base color, modulation direction and some interaction effects on the intercept and slope of the TCSFs. Specifically, the main effects of base color were driven primarily by the L- and S-cone activations. Experiment 3 replicated experiment 2 for a subset of base colors using the average luminance ratios across the fifteen participants from Experiment 1. No significant difference between visibility thresholds from both experiments was found, indicating that average luminance ratios can be used to measure and model TCSFs for chromatic flicker.

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Introduction

The visual system is one of the most complex and fascinating sensory systems of the human body and plays a crucial role in the perception of the world around us. An important feature with regards to perception, is the ability to discriminate between light of different monochromatic wavelengths or light with different spectral distributions. The colors that are perceived for these different light spectra are a purely perceptual phenomenon caused by electromagnetic radiation entering the eye, which is converted by photoreceptors to neuronal signals and subsequently processed in the brain. Colors can be strong perceptual cues, providing information about characteristics of the objects in our world. Furthermore, it is widely thought that colored light can elicit a range of biological and emotional responses (Birren, 1978).

The invention and advancement of artificial lighting has created a vast space of new possibilities and allowed the creation of light spectra and spatiotemporal light patterns not present in nature. With the continuous development of new, more versatile artificial light sources, and their ever increasing presence in our environment, it becomes necessary to take into account the characteristics of the human visual system. The current study aims to contribute to this by investigating the visual system's ability to resolve temporally modulated chromatic stimuli.

Currently, Light Emitting Diodes (LEDs) are replacing much of the more traditional lighting technologies. LEDs are relatively cost-effective, durable and efficient, and can produce a wide range of colors with high precision (Steele, 2007). An important feature of LEDs is that they make it possible to create dynamic colored lighting. However, current knowledge of how the human visual system resolves temporally modulated light stimuli is limited. Therefore, guidelines for the implementation of attractive and comfortable dynamic colored lighting applications, based on a scientific understanding of dynamic light perception are missing. In order to make dynamic lighting applications attractive and comfortable for the users, the perceived smoothness of color transitions is of major importance. However, previous studies have found that in current applications temporal color transition can be perceived as unsmooth because the human visual system resolves changes in light intensity and chromaticity at different speeds (Sekulovski, Vogels, van Beurden, and Clout, 2007). Specifically, Sekulovski et al. (2007) demonstrated that the visibility thresholds for a flicker stimulus were lower than the thresholds for perceived smoothness, highlighting the need for a temporal color model that takes into account the sensitivity of the human visual system for temporally modulated light stimuli.

In order to build such a model, it is necessary to understand the sensitivity of the visual system to temporal color contrasts at different modulation frequencies. As a step towards the development of a temporal color model, a recent study by Bueno Perez et al. (2017) examined the temporal contrast sensitivity functions (TCSFs, for a more detailed description see section 1.3) for for nine different base colors. They demonstrated that TCSFs cannot be described by a single function but are affected by chromaticity of the stimuli and individual differences between subjects. Furthermore, they confirmed previous findings that the luminous efficiency function is not sufficient to account for equal brightness of the stimuli (Kim, Mantiuk, and Lee, 2013), which had to be adjusted accordingly.

The present study replicates and extends the experimental paradigm employed by Bueno Perez et al. (2017) in order to measure TCSFs for a wide range of base colors. Furthermore, it is examined how the flicker stimuli have to be adjusted for equal brightness due to inaccuracies of the luminous efficiency function and how individual participants differ in the required adjustment. Finally, it is explored whether an average isoluminance function can be used to measure TCSFs for chromatic flicker, in order to increase the time efficiency of the experimental paradigm. In the following, the luminous efficiency function and concepts related to color perception will be discussed on the basis of previous literature. Next, empirical work examining the perception of flicker, and in specific chromatic flicker, will be reviewed, and the aims of this study are elaborated in more detail. Then, three experiments will be presented: *Experiment 1* measures individual luminance ratios to adjust for isoluminant stimuli. In *Experiment 2* visibility thresholds for isoluminant chromatic flicker stimuli are measured and modelled as TCSFs. In *Experiment 3* visibility thresholds are measured using an average isoluminance function and compared to the visibility thresholds obtained in *Experiment 2*.

1.1 The Luminous Efficiency Function

The retina of the human eye accommodates three separate types of photoreceptor cells; the rods, the cones, and the intrinsically photosensitive retinal ganglion cells (Thoreson, 2008). Only the former two, the rods and cones, are involved in vision. Rods and cones are sensitive to low and high luminance levels, respectively. Furthermore, the populations of rods and cones also differ in terms of their spectral sensitivity. Because of this, the spectral sensitivity for a human observer is different for photopic and scotopic vision.

In order to provide a perceptual analog of radiance (i.e. luminance), the International Lighting Commision (Commision Internationale de l'Eclairage, CIE) (1926) determined two spectral efficiency functions for a standard observer, CIE 1924 V(λ) for the photopic vision regime and CIE 1951 V'(λ) for the scotopic vision regime (see Figure 1.1). The V(λ) is called the luminosity or luminous efficiency curve, which represents the sensitivity with respect to the brightness for different wavelengths for a 2° field of view. Although, the luminosity function V(λ) is the current standard for photometric measures, its validity is severely constrained by large differences in spectral sensitivity between different observers. This inter-individual variation is mostly due to variations in the retinal connectivity and the contribution of the different cone-photoreceptor types (Sharpe, Stockman, Jagla, and Jägle, 2005). In addition, the V(λ) is composed as a hybrid function, artificially smoothed and matched by data for various different procedures at different laboratories. The matching of data from various procedures led to large inaccuracies that were mostly neglected, especially at short wavelengths (Sharpe et al., 2005). Moreover, the luminous efficiency differs when measured for different sizes of the visual field, with 2° and 10° most commonly used. The inaccuracies in the luminous efficiency function thus heavily confound photometric measurements and the measurement of perceptual phenomena such as flicker (Kim et al., 2013). Furthermore, the inaccuracies in the luminous efficiency function V(λ) have also impacted colorimetry. Specifically, the widely used CIE 1931 XYZ color space is based on V(λ), severely constraining its validity (Stockman, 2015). Thus in order to study color perception, color spaces can be expressed in terms of the contributions of individual cone photoreceptors (i.e. cone fundamentals; see Stockman and Sharpe, 2000), which are based on direct measurements and are not confounded by the inaccuracies in the luminous efficiency function.

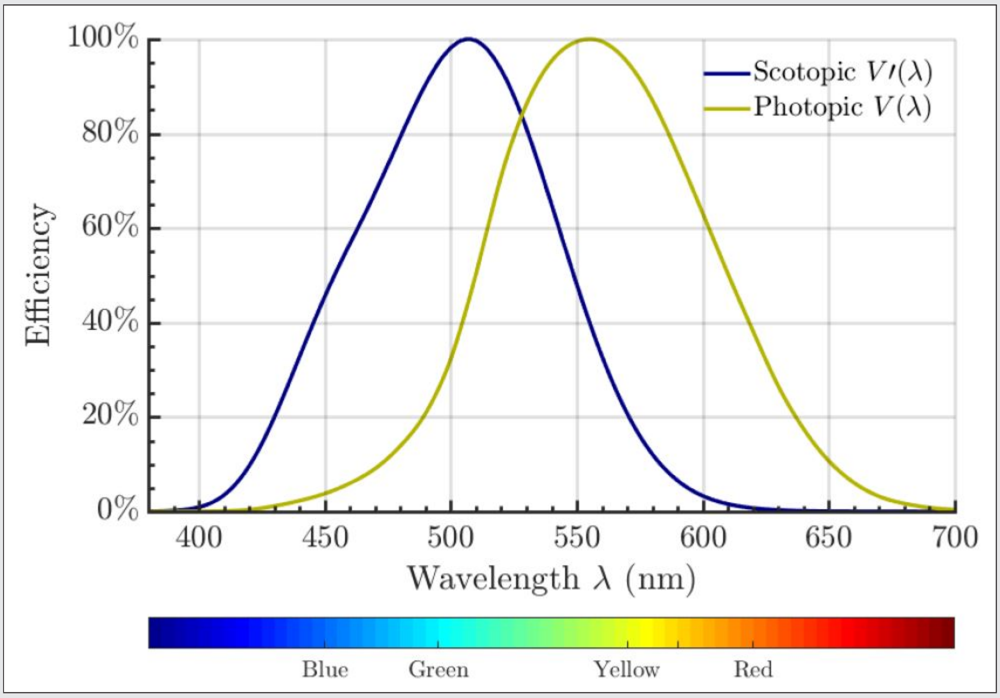


Figure 1.1: The luminous efficiency curves for photopic and scotopic vision (retrieved from Bueno Perez et al., 2017)

1.2 Color Perception

From a physiological viewpoint, the eye contains three types of cone-photoreceptors, often referred to as the L-, M-, and S-cones. The L-cones are mainly sensitive to the longer wavelengths (with a peak at 575 nm), the M-cones to the middle wavelengths (with a peak at 535 nm) and the S-cones to the shorter wavelengths (with a peak at 440 nm) (Marc and Sperling, 1977). The visual perception of color is formed by a combined activation of the three cone types relative to their spectral sensitivities upon the reception of light at a certain wavelength. These cone sensitivities or cone fundamentals have been derived from color matching functions (CMF) obtained from experiments where observers mixed and adjusted monochromatic lights to match the color of a defined target light. The most widely used CMFs are based on the work of Wright (1929) and Guild (1932), which were adopted by the CIE to create the CIE 1931 RGB color space. These CMFs were later transformed such that a linear combination of the CMFs equals the CIE 1924 $V(\lambda)$ luminosity function, resulting in the CIE 1931 XYZ color space. However, due to the inaccuracies of $V(\lambda)$ the validity of these transformed CMFs is severely constrained (Stockman, 2015). Furthermore, these CMFs are based on a 2° field of view, which does not appropriately capture normal viewing conditions. The most comprehensive set of directly measured CMFs is formed by the 10°-CMFs of Stiles and Burch (1959). These CMFs were taken as the basis of the Stockman and Sharpe (2000) cone fundamentals, which were adopted by the CIE in 2006 and form the current standard in vision research.

On the basis of CMFs several color spaces were developed. As mentioned before, a widely used color space is the CIE 1931 XYZ color space. Since this color space is not uniform other spatially uniform color spaces such as the CIE 1976 UCS color space were developed, that allow Euclidean calculations. However, as previous research has shown, current color spaces do not allow for the creation of smooth color transitions in dynamic lighting applications (Sekulovski et al., 2007). In order to create a temporally uniform color space, the human sensitivity to temporal modulations of colored light has to be investigated.

1.3 The Temporal Contrast Sensitivity Function

An important advantage of LEDs is the ability to create dynamic colored light. However, the temporal light modulations in dynamic lighting can result in visual artifacts, such as flicker. The sensitivity of the human visual system to flicker has been found to depend on the frequency of the modulation (De Lange, 1958a;De Lange, 1958b;Kelly, 1961). Above a certain critical frequency (i.e. the critical fusion frequency, CFF) the flicker stimulus fuses and is not perceived anymore, independent of its modulation size. Below the CFF, the perception of flicker depends on the modulation contrast of the stimulus as a function of the modulation frequency. This relation between contrast sensitivity and frequency is described by the temporal contrast sensitivity function (TCSF).

Flicker can be caused by a temporal modulation in luminance (luminance flicker) or in color (chromatic flicker) (Kelly, 1975). An increasing number of evidence suggests that the human visual system resolves luminance and chromatic flicker separately (e.g. Lee, Pokorny, Martin, Valbergt, and Smith, 1990; Shady, MacLeod, and Fisher, 2004; Swanson, Ueno, Smith, and Pokorny, 1987; van der Horst and Bouman, 1969). The TCSFs for luminance flicker have been found to have a band-pass characteristic (Shady et al., 2004; Swanson et al., 1987), while the TCSFs of chromatic flicker generally show a low-pass characteristic, with sensitivity decreasing for higher frequencies (Dobkins, Lia, and Teller, 1997; Granger and Heurtley, 1973; van der Horst and Bouman, 1969). Additionally, the CFF for chromatic flicker has been shown to be lower than for luminance flicker (25 Hz vs. 50 Hz; see Jiang, Zhou, and He, 2007). Both the the CFF and the TCSF are affected by stimulus features, such as stimulus size and average luminance (Bodrogi and Khan, 2012; De Valois, 2000; Kim et al., 2013; Swanson et al., 1987; Wooten, Renzi, Moore, and Hammond, 2010). For example, it was found that peak sensitivity and filter characteristics for chromatic and luminance flicker are differently affected by different mean luminance levels up to 31.83 cd/m^2 (Swanson et al., 1987).

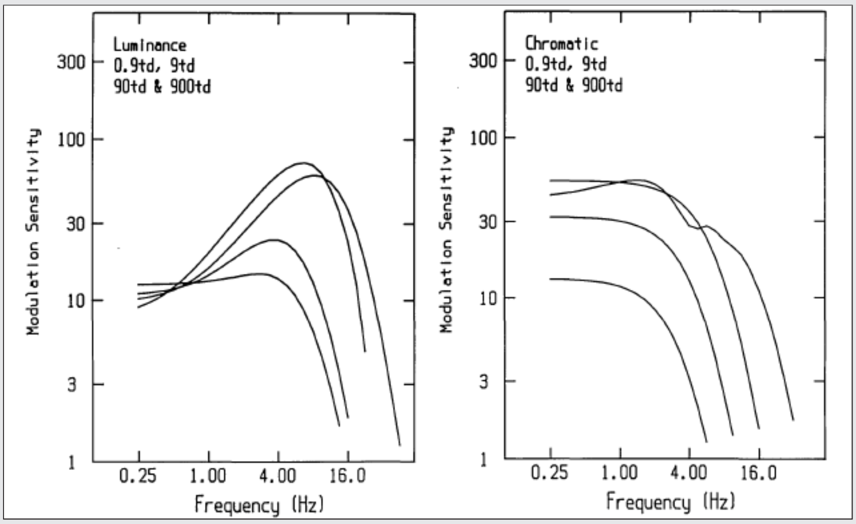


Figure 1.2: Modulation sensitivity as a function of frequency (Hz) for luminance (left) and chromatic (right) flicker. The luminance levels were measured in trolands (td) that correspond to 0.31 cd/m^2 (Swanson et al., 1987)

1.4 Chromatic Flicker

The findings mentioned before highlight the importance to investigate sensitivity to luminance and chromatic flicker separately. However, in order to measure chromatic flicker, the luminance of the flicker stimulus needs to be kept constant. In some studies a small decrease in sensitivity for low frequencies was found for the TCSFs of chromatic flicker (Lou, 2016; Shady et al., 2004). This band-pass characteristic could be explained by stimuli not being equal in brightness, resulting in visible luminance flicker (Kim et al., 2013). Previous research has shown that the luminous efficiency function V(λ) used in photometric measurements does not accurately capture the sensitivity of individual observers, especially for short wavelengths (e.g. Kim et al., 2013; Sharpe et al., 2005). This can lead to a different brightness for two colored lights with the same luminance within and between different observers. When chromatic stimuli are adjusted such that they have the same brightness they are referred to as being isoluminant. Due to the inter-individual differences between observes, isoluminant stimuli have to be defined for each observer individually (Metha and Mullen, 1996). To adjust the chromatic flicker stimuli for isoluminance, heterochromatic flicker photometry (HFP) can be used. With this method, the luminance ratio between two alternating lights is adjusted until a minimum amount of luminance flicker is perceived. Since the CFF for luminance flicker is higher than for chromatic flicker (Jiang et al., 2007), the effect of luminance flicker can be isolated by choosing a frequency above the CFF for chromatic flicker (Bone and Landrum, 2004).

Using HFP thus allows to study the sensitivity to chromatic flicker in isolation, without any confounding effects of luminance flicker. While the sensitivity to luminance flicker has been studied extensively, only some work on modelling the TCSFs for chromatic flicker has been done. For example, Dobkins et al. (1997) found that an exponential function was sufficient to describe the TCSF for chromatic flicker. Other studies focussed on modelling the TCSFs for flicker stimuli that address only some part of the visual system, for example, red-green opponency (Eskew, Stromeyer, and Kronauer, 1994). Most of the studies that have investigated chromatic flicker only studied stimuli limited in chromaticity (e.g. red-green chromatic flicker), due to technical limitations at the time. Moreover, only a few studies that measured chromatic flicker have controlled for isoluminant stimuli (Mullen, 1985).

One recent study investigating chromatic flicker perception while adjusting for isoluminance was that of Bueno Perez et al. (2017). They measured the detection threshold of chromatic flicker for nine base colors (in the CIE 1976 UCS diagram), four modulation directions, and seven flicker frequencies using the method of adjustment, for a 10° field of view. Special care was taken to minimize confounding effects of luminance flicker using HFP. In the first experiment, each flicker stimulus was modulated using a sinusoidal wave between two colors with a distance of 0.05 $\Delta(u', v')$ (centered around a specific base color) at a frequency of 25 Hz. Participants were instructed to adjust the luminance ratio between the two extreme colors of the stimulus until flicker was no longer perceived or minimized. In the next experiment, participants were presented with chromatic flicker stimuli adjusted for isolumiance (with the participant-specific luminance ratios obtained from HFP). Participants had to adjust the chromatic modulation amplitude until flicker was just not perceivable anymore. Based on the indicated detection thresholds of each participant, TCSFs were calculated and analyzed for the different conditions. The results showed that the luminance ratios required for isoluminance were significantly different from 1 for some conditions. Moreover, luminance ratios differed substantially between participants. In line with Dobkins et al. (1997), the TCSFs could be modelled as an exponential function, that is, contrast sensitivity exponentially decreased with increasing frequency. Moreover, significant effects of participant, base color, modulation direction, and the interaction between base color and direction on the slopes and intercepts of the models the were found.

The study of Bueno Perez et al. (2017) has two important implications for the research of chromatic flicker perception, which were addressed in the present study. First, the study's results show that human sensitivity to chromatic flicker cannot be described by one single function but depends on the chromaticity of the base color and the modulation direction. Thus, it is necessary to identify the TCSFs of a wide range of base colors. Second, it demonstrated that for isoluminance, the luminance ratios between color stimuli are significantly different from one in some cases. This implies that $V(\lambda)$ does not accurately capture the human spectral sensitivity and needs to be corrected to ensure chromatic isoluminance. As mentioned earlier, this is in line with previous studies yielding similar conclusions (e.g. Kim et al., 2013; Sharpe et al., 2005). The research goals, hypotheses and research questions of the present study will be outlined in more detail in the next section.

1.5 Research Goals

Measuring TCSFs for a Wide Range of Base Colors

The major research goal of the present study was to measure individual TCSFs for a wide range of base colors. In order to measure a large amount of data, the efficiency (e.g., the time needed for measuring a certain number of data) of the experiment is crucial. Based on the findings of Bueno Perez et al. (2017), the relation of visibility thresholds and frequency can be accurately described by an exponential function (linear on a log-scale), meaning that only a limited number of frequencies should be sufficient to determine the relationship. Thus, more efforts could be made for exploring more base colors. Based on previous findings we expected that the TCSFs can be described by an exponential model for a wide range of base colors.

Inter-Individual Variance for Isoluminance

A second research goal was investigate individual differences in the luminance ratios needed to adjust for isoluminant flicker stimuli. A new function, D(λ), which reflects for each wavelength how the the (relative) luminance needed to be adjusted for isoluminance using HFP for individual participants, was proposed by Bueno Perez et al. (2017). It was found that most adjustments occurred in the short and long wavelengths regions. Interestingly, this distribution varied between participants to some extent. However, given the small sample size ($N = 3$), no conclusive statements about the between-subject variance of this function and which base colors contribute most to the variance can be made. Findings of comparable previous research in flicker perception (e.g., Perz, Sekulovski, Vogels, and Heynderickx, 2017; Perz et al., 2014; Sharpe et al., 2005) have indicated that the visibility thresholds of different flicker measures generally vary between participants. It can therefore be expected that D(λ) will show inter-individual variance. To our knowledge, no efforts have been made to address this issue in chromatic flicker research. In the present study, the inter-individual variance in luminance ratios and the resulting D(λ) is investigated for a larger sample size ($N = 15$). Based on previous research, we hypothesized that these measures would vary between participants.

Using an Average Isoluminance Function to Measure Chromatic Flicker

A third aim of the study was to test whether an average isoluminance function can be used to measure individual TCSFs, in order to improve the efficiency of the experimental procedure. As mentioned above, due to individual differences, measuring luminance ratios for each participant is necessary, which reduces the efficiency of the chromatic flicker experiment significantly. Previous research has shown that despite inter-individual variation, average visibility thresholds can be used to accurately model thresholds as a function of frequency for the stroboscopic effect (Perz et al., 2014) and for periodic luminance flicker (Perz et al., 2017). Therefore, it would be advantageous and interesting to explore whether an average isoluminance function is good enough to ensure isoluminance for all participants.

Method

The present study measures the TCSF for isoluminant chromatic flicker stimuli. In this section the three experiments and procedures that were used in this study will be described.

2.1 Experimental Setup

The flicker stimuli were generated by a customized LED flicker system. The system consisted of a large wooden cuboid box with 36 XP-E LEDs (12 red, 8 green, 16 blue LEDs) mounted at the back side of the front panel. The stimuli were displayed through a circular hole with a diameter of 26.4 cm, covering a 10° field-of-view for participants when seated at a distance of 150 cm in a fixed position (i.e. by means of a chin rest). To ensure diffuse reflection of the light inside the box, the interior of the box was painted in matte white color. By this, a homogenous distribution of the light emitted by the LEDs could be obtained. The LEDs in the apparatus were controlled using an Arduino Due microcontroller to generate high-frequency Pulse Width Modulated (PWM) signals with high precision (2 kHz driving frequency and 16-bit dimming). The target stimuli were defined in the CIE 1976 UCS color space and were transformed to device dependent RGB color space of the LEDs. A standard keyboard was provided for participants to enter their responses. The entire setup is displayed in Figure 2.1.

Before the experiment, the system was calibrated using a JETI Specbos 1201 measuring device for a 10° circular field. The JETI spectrometer was put in front of the LED system at a distance of 150 cm and a height of 131.5 cm, pointed to the center of the stimulus field. Note that the system had to warm up for at least one

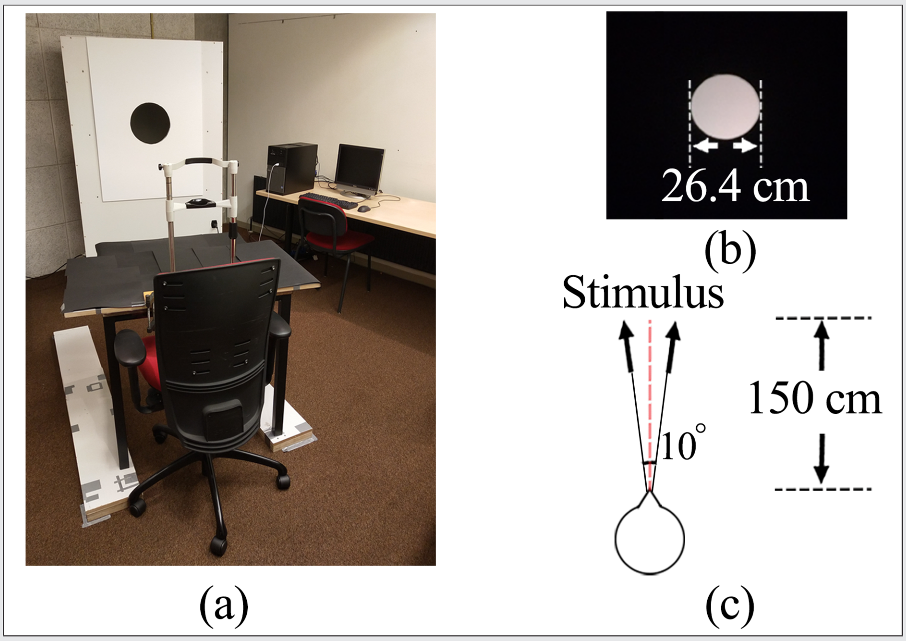


Figure 2.1: Experiment Setup

hour to reach a stable output of the LEDs before calibration. During warm-up the PWM values of the LEDs were set to their maximum. After calibration the spectral power distributions measured by the spectrometer and the distributions calculated based on the calibration file were compared. Figure 2.2 depicts the measured and calculated spectral distributions for each stimulus base color used in the present study (for a more detailed description of the stimuli see section 2.2: General Stimuli), indicating a nearly perfect match. From the calibration file three chromaticity points in the CIE 1931 XYZ color plane corresponding to the system gamut for red, green and blue were obtained. These values were subsequently transformed into the CIE 1976 UCS color space to define the range of possible stimuli.

2.2 General Stimuli

Each flicker stimulus consisted of a sinusoidal temporal modulation around a base color specified in the CIE 1976 UCS (u',v') diagram in a specified modulation direction, with a certain modulation amplitude and at a specified frequency (see Figure

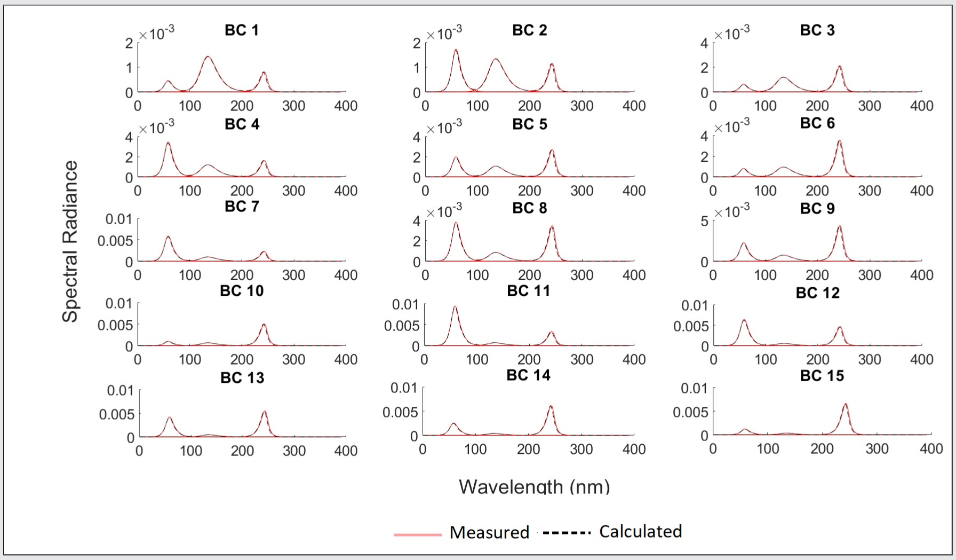


Figure 2.2: Calculated vs. measured spectral power distributions for all fifteen base colors

2.3). The luminance of the stimuli varied at the same frequency in order to make the stimuli isoluminant for the observer, with an average average luminance of 37.5 cd/m^2.

Fifteen base colors (BC_1 to BC_{15}) were chosen to cover as much of the color space as possible without overlap and staying within the gamut of the device (see Figure 2.4). The colors were equally distributed across a triangle with its endpoints in the green, blue and red region of the color space. Note that the blue and red endpoints were chosen to be less saturated, due to the complications reported by Bueno Perez et al. (2017) for the flicker perception and adjustment for more saturated colors. The spectral distribution of the fifteen base colors can be seen in Figure 2.2, where base colors BC_{15}, BC_1, and BC_{11} correspond to the maximum red, green, and blue endpoints of the triangle. All other base colors in between this triangle are a combination of these three primaries.

Four modulation directions were selected, that is, Direction 0° (corresponding to a modulation parallel to the u'-axis), Direction 90° (corresponding to a modulation parallel to the v'-axis), Direction 45° and Direction 135°. In *Experiment 1* the

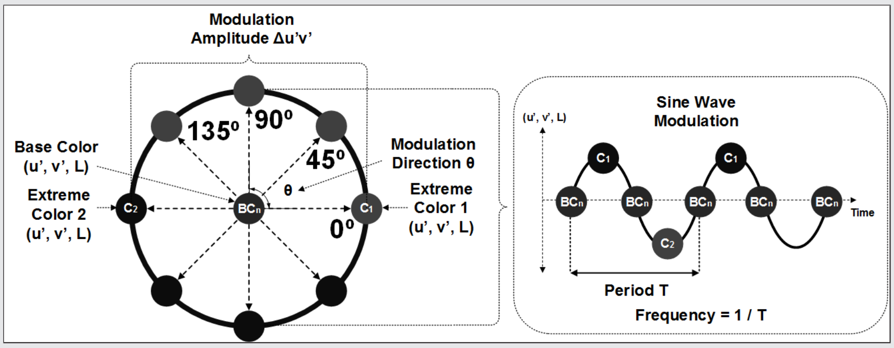


Figure 2.3: Schematic overview of the sinusoidal stimulus modulation (taken from Bueno Perez et al., 2017)

modulation amplitude was fixed at 0.05 $\Delta(u',v')$ and the frequency was fixed at 25 Hz. In *Experiment 2* and 3 the modulation amplitude could vary between 0.0003 $\Delta(u',v')$ up to 0.06 $\Delta(u',v')$. For different modulation amplitudes, the luminance ratio was calculated by means of a simple exponential function (Bueno Perez et al., 2017). Three values for the frequency were selected as explained below.

2.2.1 Frequency Selection

Previous studies suggested that the sensitivity function for isoluminant chromatic flicker can be modelled as an exponential function of frequency (Bueno Perez et al., 2017). Since this exponential relationship can be expressed as linear on a logarithmic scale, two frequencies can be used to accurately measure the TCSFs. In order to include a measure of error to test the goodness-of-fit of the models, at least three frequencies are needed. To determine which frequencies to use, linear regression models were fitted to the data from the study of Bueno Perez et al. (2017) for all possible three and four frequency combinations of the seven frequencies (i.e., 2, 4, 8, 10, 15, 20, 25 Hz) and compared to the model using all seven frequencies. Similar to their study, the TCSFs were modelled with the reciprocal of the contrast sensitivities expressed as ΔLMS, since the TCSFs with this contrast measure were reported to result in the highest goodness-of-fit. The performance of the fitted models was analyzed by comparing them with the model for seven

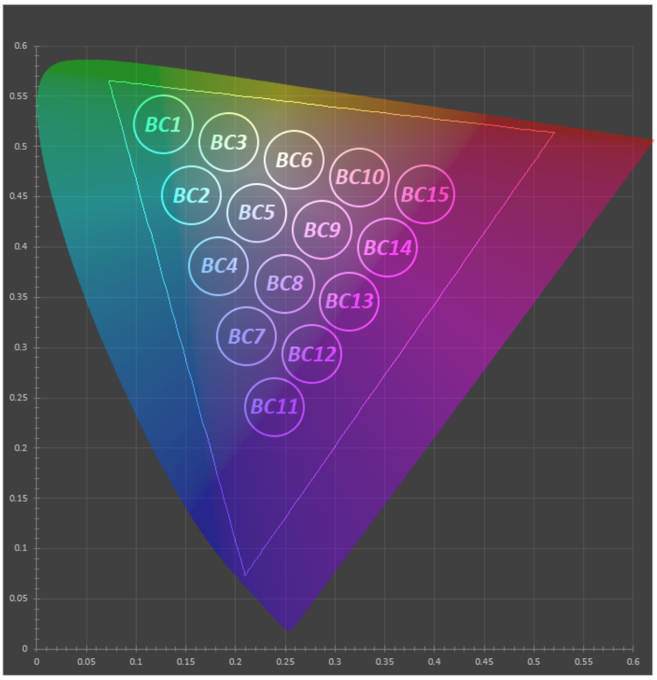


Figure 2.4: Distribution of the fifteen base colors in the CIE 1976 UCS diagram

frequencies to obtain goodness-of-fit statistics (R^2). The R^2 of each model were then averaged across conditions in order to compare the overall performance of the models. Suitable frequency combinations were identified by selecting the best performing model for all participants. Initially a four frequency model with 2 Hz, 8 Hz, 15 Hz and 25 Hz was chosen as it resulted in the best fit. However, during a short pilot experiment testing the selected frequencies on the stimuli used in the present study, it was found that for 25 Hz in some conditions no flicker could be observed at the highest possible modulation amplitude. We therefore decided to use the next best fitting model with 20 Hz as the maximum frequency and three frequencies due to time limitations. The final frequencies chosen for the present study were 2 Hz, 8 Hz, and 20 Hz. The final stimulus parameters are displayed in Table 2.1. An overview of the parameters used the three experiments is provided in Table 2.2.

Base Colors	u'	v'	Modulation Direction	Frequency
1	0.1273	0.5213		
2	0.1553	0.4512		
3	0.1929	0.5039		
4	0.1833	0.3811		
5	0.2209	0.4338	0°	
6	0.2586	0.4865		2 Hz
7	0.2113	0.3110	45°	
8	0.2489	0.3637		8 Hz
9	0.2866	0.4164	90°	
10	0.3242	0.4691		20 Hz
11	0.2393	0.2409	135°	
12	0.2769	0.2936		
13	0.3146	0.3463		
14	0.3522	0.3990		
15	0.3899	0.4517		

Table 2.1: General stimulus parameters

	Base Colors	Mod. Directions	Frequencies	Mod. Amplitudes
Exp. 1	$BC_1 - BC_{15}$	0, 45, 90, 135°	25 Hz	$.05\ \Delta(u',v')$
Exp. 2	$BC_1 - BC_{15}$	0, 45, 90, 135°	2, 8, 20 Hz	$.0003 - .06\ \Delta(u',v')$
Exp. 3	BC_7, BC_{13}, BC_{14}, BC_{15}	0, 45, 90, 135°	2, 8, 20 Hz	$.0003 - .06\ \Delta(u',v')$

Table 2.2: The stimulus parameters for each experiment

2.3 Experiment 1

In this experiment the luminance ratio between the extreme colors of the chromatic modulation at which minimal luminance flicker is perceived was measured for all combinations of base color and modulation direction. The luminance ratios were measured to ensure isoluminant stimuli in the second experiment and to analyze the inter-individual variance in luminance ratios between participants.

2.3.1 Design

A within-subject design was employed to measure the luminance ratios at which minimal flicker is perceived for 120 different conditions: 15 base colors × 4 modulation directions × 2 starting luminance ratios × 1 modulation amplitude × 1 frequency.

2.3.2 Participants

Fifteen participants (5 female and 10 male), who were all students from Eindhoven University of Technology, participated in the experiment. Among those, three were researchers of this study and the other twelve were recruited through the university participant database or face-to-face contact. All participants had normal color vision, as indicated by the Ishihara test for color blindness. Besides, no participant had a prior history of migraine or epilepsy.

The participants were aged from 21 to 27 years old, with an average age of 23.3 years (SD = 1.79). Five of the participants had corrected vision and wore contact lenses or glasses during the experiment. The three researchers of this study are all male, with the age of 23, 23 and 24 years old. One of the three had corrected vision and was wearing contact lenses during the experiment.

2.3.3 Stimuli

The flicker stimuli consisted of the base colors modulated at a fixed amplitude of 0.05 $\Delta(u',v')$ and frequency of 25 Hz, with luminance ratios adjusted by the participants. For all conditions stimuli were presented once with a low and once with a high starting luminance ratio of 0.8195 and 1.2201, corresponding to values where flicker is clearly visible, in order to minimize anticipation effects.

2.3.4 Procedure

Before the start of the experiment, participants received an introduction to the procedure and any unclarities were resolved. They were asked for a prior history of epilepsy and the Ishihara test was administered. Eligible participants proceeded to perform a few practice trials to get familiar with the procedure. After the practice phase the experiment started.

During the experiment, participants were presented with a flicker stimulus at a specific base color with either a high or low starting luminance ratio. For each base color a two-minute adaptation period at the chromaticity of the base color was included before the flicker stimuli were presented. In order to measure the luminance ratios at which no or minimal flicker was perceived, the method of adjustment was used. It has been found to be an efficient and reliable method for measuring visibility thresholds for chromatic flicker (Kong, Vogels, Sekulovski, and Heynderickx, 2018) and was used by Bueno Perez et al. (2017). The method of adjustment allowed the participants to regulate the luminance ratio and alter it to a point of minimal flicker. The ratio could be adjusted in either a large step or a small step corresponding to an approximate change of 5% and 1%, respectively, using the arrow keys on a standard keyboard. The point of minimal flicker was determined when participants pressed the *Enter*-key on the keyboard and the following stimulus condition was presented.

The experiment was divided in four blocks of measurement (ca. 15–20 min per block) with rest in a daylit environment in between (ca. 5–15 min, as preferred by the participant), in order to minimize fatigue and eye-strain. In the first block three base colors and in the remaining blocks four base colors were presented. The order of base colors was counterbalanced between participants using a Latin-square design and the order of modulation directions and starting luminance ratios was randomized within participants.

2.4 Experiment 2 and Experiment 3

2.4.1 Design

In both experiments a within-subject design was employed to measure the visibility thresholds at which chromatic flicker is just perceived. In *Experiment 2* individual luminance ratios and in *Experiment 3* averaged luminance ratios were used. There were 360 different conditions (15 base colors × 4 modulation directions × 3 frequencies × 2 starting modulation amplitudes) in *Experiment 2* and 96 conditions (4 base colors × 4 directions × 3 frequencies × 2 starting amplitudes) in *Experiment 3*.

2.4.2 Stimuli

The stimuli consisted of the base colors modulated at three different frequencies (i.e. 2 Hz, 8 Hz, and 20 Hz). In *Experiment 2* all base colors were included, while in *Experiment 3* only four base were used. These were selected based on the largest standard deviation of the corresponding luminance ratios across all 15 participants from *Experiment 1*. Furthermore, in *Experiment 2* the luminance of the two extreme colors of a stimulus was adjusted for isoluminance with the corresponding luminance ratio for each participant, whereas in *Experiment 3* the average luminance ratio across all participants from *Experiment 1* was used. For the adjustment procedure, stimuli were presented with two starting amplitudes where chromatic flicker is not perceivable or clearly visible (i.e. 0.0005 $\Delta(u',v')$ and 0.05 $\Delta(u',v')$, respectively).

2.4.3 Procedure

In both experiments only the three researchers of the study participated, due to time limitations. Because the participants were the researchers of this study no practice phase or pre-testing was required. During the experiments, participants were presented with flicker stimuli for all base colors in *Experiment 2* and for four selected base colors in *Experiment 3*. For each base color a two-minute adaptation period was included before the flicker stimuli were presented. In order to measure the visibility thresholds for each stimulus, the method of adjustment was used. This allowed participants to regulate the modulation amplitude and alter it to the point at which flicker was just not visible. The point of just noticeable difference was documented and taken as a measure of sensitivity. Participants adjusted the modulation amplitude using the arrow keys on a keyboard. The amplitude could be adjusted in either a large step or a small step corresponding to an approximate change of 5% and 1%, respectively. The threshold value was determined when participants pressed the 'Enter'-key on the keyboard and the following stimulus condition was presented.

Experiment 2 was divided in eight blocks of measurement (ca. 15–30 min per block) with rest in between or distributed over several days, in order to minimize fatigue and eye-strain. In each block except for one, two base colors were presented. *Experiment 3* was divided in two blocks of measurement (ca. 30 min per block) with rest in between. Due to the small number of participants no counterbalancing of the order of base colors was applied. The order of modulation directions and starting amplitudes was randomized within participants.

Analysis and Modelling

3.1 Experiment 1

The luminance ratios were averaged over the two starting luminance ratios for each condition (i.e. base color and direction). Luminance ratios that were three scaled median absolute deviations (MAD) away from the median were considered as outliers and removed from the data. The resulting luminance ratios were analyzed for between-subject variance and the effect of *Base Color* and *Modulation Direction* on *Luminance Ratio* was tested using a repeated measures ANOVA, with the within-subject factors *Base Color* (BC_1–BC_{15}) and *Modulation Direction* (0°, 45°, 90°, 135°). Post-hoc analyses with Bonferroni correction were performed for the significant effects wherever possible.

Furthermore, to examine how the L-, M-, and S-cone activations were adjusted by the measured luminance ratios in order to yield equal brightness of the stimuli, for each participant a D(λ) function was calculated. It was defined as the sum of the absolute difference in spectral power distributions ΔSPD of the two extreme colors of the chromatic flicker modulation weighted by the logarithm of the corresponding luminance ratio R over all conditions (see Equation 3.1). If the luminous efficiency function V(λ) was correct, no luminance ratio adjustment would be required (ratio = 1) and D(λ) would be zero (log(1) = 0). Therefore, D(λ) function can be interpreted as the adjustment of the cone fundamentals necessary to match equal luminance as defined by the V(λ) luminous efficiency function. However, in order to compare the how much the individual L-, M-, and S-cone activations are adjusted relative to each other, D(λ) had to be normalized by the unweighted sum of the differences S(λ) (see Equation 3.2). This resulted in individual adjustment ratios of the D(λ) L-, M-, and S-cone activations. Specifically, the differences in adjustment ratio between the D(λ) L-, M-, and S-cone activations indicated which cone activations were adjusted more by the luminance ratios relative to each other.

$$D(\lambda) = \sum_i \log(R_i) * |(SPD_{C1} - SPD_{C2})| \tag{3.1}$$

$$S(\lambda) = \sum_i |(SPD_{C1} - SPD_{C2})| \tag{3.2}$$

3.2 Experiment 2 and Experiment 3

In both experiments detection thresholds for chromatic flicker were obtained. The thresholds were transformed into a contrast sensitivity measure. The visibility thresholds obtained were expressed in the CIE 1976 UCS color space, which had to be transformed to a measure of contrast sensitivity in order to model the TCSFs. Based on previous studies (Bueno Perez et al., 2017) the contrast sensitivity was calculated as the reciprocal of the detection thresholds expressed as chromatic contrast using Equation (3.3).

$$\Delta LMS = \sqrt{\Delta L^2 + \Delta M^2 + \Delta S^2} \tag{3.3}$$

with Δ L, Δ M, and Δ S representing the difference in L-, M-, and S-cone activations for the two extreme colors of the flicker stimulus modulation for the corresponding condition, and the modulation amplitude is expressed as the detection threshold. The L-, M-, S- cone activations were calculated using the Stockman and Sharpe (2000) cone fundamentals. In order to analyze the contrast sensitivities on a linear scale, they were log-transformed with the natural logarithm. The contrast sensitivity thresholds were analyzed as a function of frequency to obtain the TCSFs for each condition. To this end the log-transformed contrast sensitivities were fitted with a linear model, resulting in 56 TCSFs (15 base colors $\times$ 4 modulation directions). Mean goodness-of-fit statistics were calculated and compared between base colors and participants. Note that for the modelling of the TCSFs, thresholds were not averaged between starting amplitudes. This was done in order to avoid introducing a bias by the calculation of a standard average, given the observed difference between thresholds for some conditions.

Results

4.1 Experiment 1

During this experiment, the luminance ratios at which minimal flicker was perceived were measured for 60 conditions (15 base colors × 4 directions) and two starting amplitudes, resulting in 120 luminance ratio measurements for each participant. One extreme luminance ratio was identified as an outlier based on the MAD (see section 3: Analysis and Modelling) and visual inspection of the data, and was excluded for further analysis.

4.1.1 Luminance Ratios

Luminance ratios were analyzed for effects of participant, *Base Color* and *Modulation Direction*. A repeated-measures ANOVA revealed significant main effects for *Base Color* ($F_{14,14}$ = 27.18; p < .001; η^2 = .66), and *Modulation Direction* ($F_{14,3}$ = 4.42; p < .001; η^2 = .0.24), as well as a significant interaction between *Base Color* and *Modulation Direction* ($F_{14,42}$ = 31.86; p < .001; η^2 = .70). Furthermore, the between-subjects term was significant ($F_{14,14}$ = 39.04; p <. 001; η^2 = .86), indicating differences in luminance ratios between participants. Appendix A provides the mean and standard deviation of luminance ratios for *Base Color* and *Modulation Direction*.

To better understand the main effect of *Base Color*, the *Luminance Ratio* was plotted as a function of *Base Color* (BC_1 – BC_{15}) and as a function of the L-, M-, and S-cone activations corresponding to the base colors (see Figure 4.1). It can be observed that *Luminance Ratio* decreases from BC_1 to BC_{15}. Post-hoc pairwise comparisons of the predicted margins confirm this trend with a significant difference between BC_1 and BC_{15} and between a majority of successive base colors. The figure also shows that a negative effect of *Base Color* is mainly driven by the L- and S-cone activations for each base color. This indicates that the luminance ratio of a stimulus had to be adjusted more (relative to a ratio of one) for base colors with higher L- and S-cone activations, in order to minimize luminance flicker. Furthermore, to test whether *Base Color* also had an effect on the magnitude of the variation between participants, the standard deviation was analyzed as a function of base color. A linear regression shows that the standard deviation slightly increased from BC_1 to BC_{15} ($\beta = 0.0009$; $p < .001$; $R^2 = .44$).

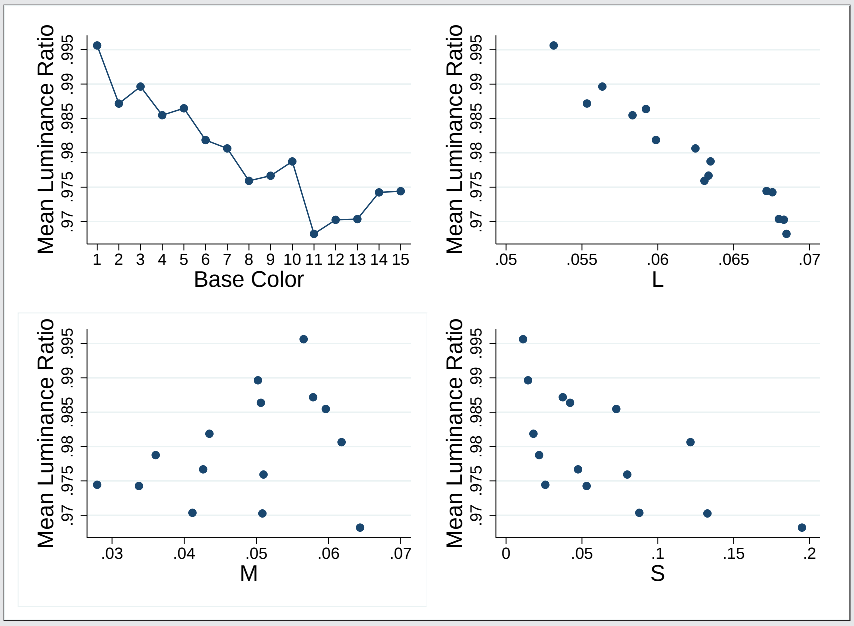


Figure 4.1: Main effect of *Base Color* and the L-, M-, and S-cone activations for each base color on the luminance ratios measured in *Experiment 1*

Post-hoc tests on the predicted margins for the main effect of *Modulation Direction* show significant differences between all directions except for Direction 45° and Direction 90°. The *Luminance Ratio* decreased from Direction 135° (Mean = 0.989, *SD* = 0.025) to Direction 0° (Mean = 0.985, *SD* = 0.034), Direction 90° (Mean = 0.973, *SD* = 0.017) and Direction 45° (Mean = 0.971, *SD* = 0.028).

A visual inspection of the interaction effect between *Base Color* and *Modulation Direction* shows that the main effect of *Modulation Direction* was mainly driven by this interaction effect. Figure # shows the predicted margins for *Base Color* and *Modulation Direction*. Four main observations can be made from this graph: First, Direction 0° and Direction 45° follow a similar trend (i.e the lines are roughly parallel) and these same holds for Direction 90° and Direction 135°. However, both pairs follow an opposite jagged pattern, that is, high values for one pair correspond to low values for the other and vice versa. Second, in line with the main effect of *Base Color*, a decreasing trend towards BC_{15} can be observed. Third, in line with the main effect of *Modulation Direction*, Direction 0° and Direction 135° show the most extreme values, with the highest luminance ratio for Direction 0° at BC_1 (1.017) and the highest luminance ratio for Direction 135° for BC_{15} (1.027). Fourth, and most interestingly, both pairs, follow a jagged pattern that corresponds to the triangular distribution of the base colors in the CIE 1976 UCS color space (see Figure 2.4). Specifically, for Direction 0° and Direction 45° luminance ratios decreased for base colors towards the axis of the triangle from BC_1 to BC_{15} and increased for base colors towards the axis of the triangle from BC_1 to BC_{11}, and vice versa for Direction 90° and Direction 135°. An analysis in LMS color space shows that Direction 0° and Direction 135° show opposite patterns for the difference in M- and S-cone activations (ΔM, ΔS) of the modulation for each base color (see Figure 4.2), but show a similar pattern for difference in the L-cone activations (ΔL). Specifically, ΔM is higher for Direction 0°, following the jagged pattern corresponding to the triangular base color distribution, while ΔM is lower for Direction 135° and stays nearly constant. The opposite pattern can be observed for ΔS. Although these findings potentially underlie the main effect of *Base Color*, they do not fully explain it. Because a more detailed analysis would have been beyond the scope of this study no further analyses were conducted.

4.1.2 Deviation from the Luminous Efficiency Function: D(λ)

In order to further investigate how the individual cone fundamentals were adjusted by the luminance ratios, the D(λ) function was calculated for each participant (see

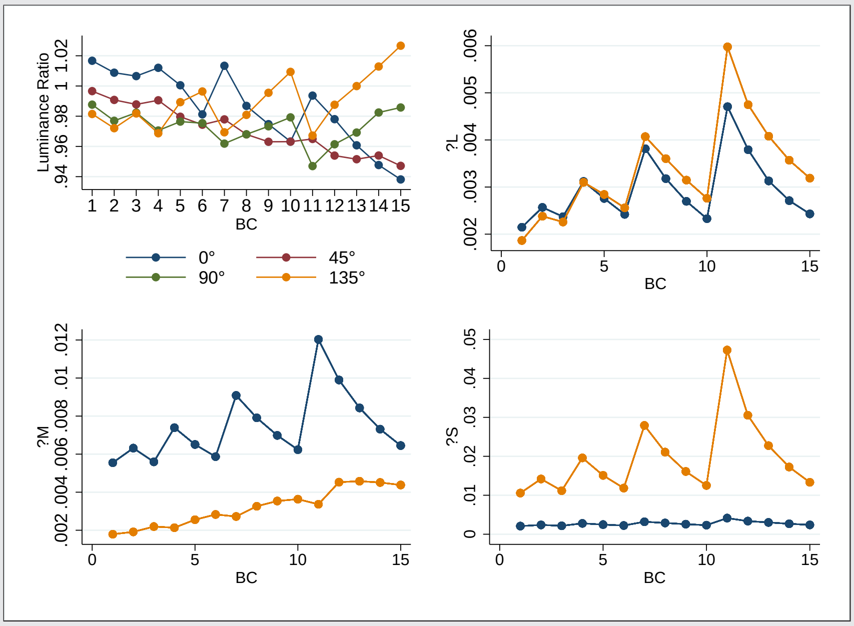


Figure 4.2: Top left: Interaction effect of *Base Color* × *Modulation Direction* on the luminance ratios measured in *Experiment 1*. **Top right, bottom left, bottom right:** ΔL, ΔM, and ΔS as a function of base color for Direction 0° and Direction 135°

section 3: Analysis and Modelling). The D(λ) function was then normalized by S(λ) (i.e. the unweighted sum of the differences in SPDs of the flicker modulation) to obtain individual adjustment ratios for the D(λ) L-, M-, and S-cone activations. Figure 4.3 shows the D(λ) and S(λ) functions for one participant. The figure shows that overall the stimulus modulations activated mostly the L- and S-cones (see S(λ). For this participant, the D(λ) functions suggests that the S-cones were adjusted more relative to the L- and M-cones. However, in order to obtain the relative ratio of adjustment for each cone type, the normalized D(λ) cone activations had to be compared. Figure 4.3 shows the individual D(λ) adjustment ratios averaged across participants. It can be seen that the adjustment ratio for the S-cones (Mean = 0.030, *SD* = 0.008) is slightly higher than for the L- (Mean = 0.027, *SD* = 0.008) and M-cones (Mean = 0.027, *SD* = 0.007), however, this difference was not significant as determined by Bonferroni corrected pairwise comparisons (all $p > .912$).

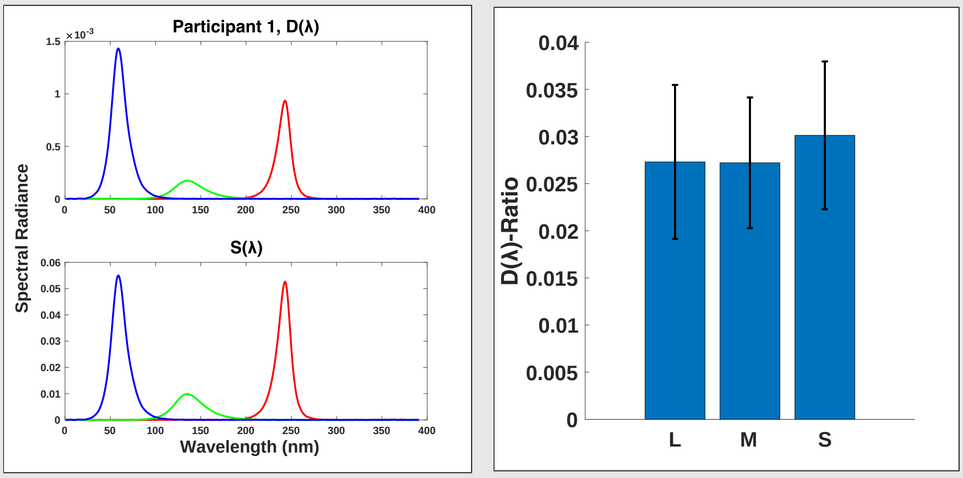


Figure 4.3: Left: D(λ) for one participant and the total sum of the differences in SPDs of the flicker modulation S(λ). **Right:** the D(λ)-adjustment ratio averaged across participants

4.2 Experiment 2

In this experiment, the chromatic flicker detection thresholds were obtained for 360 conditions (15 base colors × 4 modulation directions × 3 frequencies × 2 starting amplitudes). The thresholds were expressed in the CIE 1976 UCS diagram.

Figure 4.4 shows the fitted regression models and their confidence intervals for a single participant (for the TCSFs for all participants see Appendix B). The figure shows that overall the linear fits are quite accurate. However, for some conditions large distances between the threshold values for both starting amplitudes can be observed. Moreover, for some conditions a band-pass shape can be observed, with higher thresholds for 8Hz compared to 2Hz, suggesting some remaining luminance flicker. In total, for 41 of the 540 (180 x 3 participants) conditions this band-pass shape was observed, with more than half for BC_{13} (8), BC_{15} (5) and BC_{15} (10). This is also reflected in the goodness-of-fit (R^2) of the models, which is shown in Table 4.1 for each base color and all participants. While the average R^2 for participant 1 and 3 are higher than 0.69 for all base colors, some very low R-squares can be observed for participant 2, with values lower than 0.57 for BC_{12} to BC_{15}.

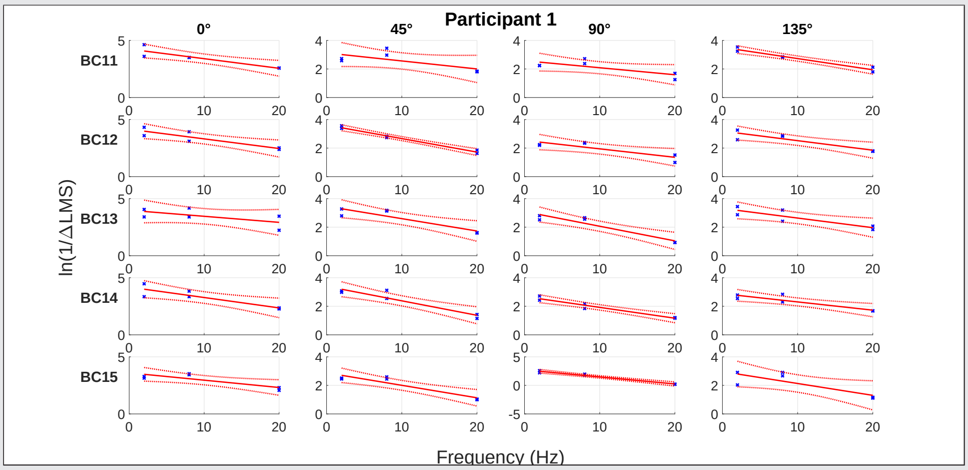


Figure 4.4: Fitted TCSFs measured in *Experiment 2* for five base colors and the four modulation directions for one participant. Visibility thresholds are plotted for both starting amplitudes

Regarding *Intercept*, main effects were found for *Base Color* ($F_{2,14} = 4.03$; $p < .001$; $\eta^2 = .67$) and *Modulation Direction* ($F_{2,3} = 49.68$; $p < .001$; $\eta^2 = .96$), as well as a significant interaction between *Base Color* and *Modulation Direction* ($F_{2,42} = 5.23$; $p < .001$; $\eta^2 = .72$). Furthermore the between-subjects term was significant ($F_{2,2} = 25.82$; $p <. 001$; $\eta^2 = .65$), indicating differences in *Intercept* between participants. A visual inspection of the effect of *Base Color* (see Figure 4.5) suggests a relation between the intercepts and the relative location of the base colors in the triangle spanned by the base colors BC_1, BC_{11} and BC_{15} in the CIE 1976 UCS diagram. Specifically, intercepts decreased for base colors towards the axis from BC_1 to BC_{15} and increased for base colors towards the axis from BC_1 to BC_{11}. Post-hoc tests for the main effect of *Modulation Direction* show a significant difference between all directions, except between Direction 45° and Direction 135°. Specifically, the intercept decreases from Direction 0° (Mean = 4.64, *SD* = 0.57) to Direction 135° (Mean = 3.56, *SD* = 0.68), Direction 45° (Mean = 3.56, *SD* = 0.63) and Direction 90° (Mean = 2.91, *SD* = 0.43). Due to the large amount of factor levels, the interaction effect was very difficult to interpret and was not considered further.

Regarding slope, a main effect was found for *Base Color* ($F_{2,14} = 5.83$; $p < .001$;

	ID			
Base Color	1	2	3	Mean
BC$_1$	0.75	0.92	0.92	0.86
BC$_1$	0.93	0.96	0.95	0.95
BC$_1$	0.93	0.96	0.78	0.89
BC$_1$	0.92	0.94	0.95	0.94
BC$_1$	0.95	0.92	0.93	0.93
BC$_1$	0.93	0.89	0.95	0.92
BC$_1$	0.91	0.84	0.94	0.90
BC$_1$	0.87	0.64	0.87	0.79
BC$_1$	0.92	0.70	0.93	0.85
BC$_1$	0.91	0.76	0.92	0.86
BC$_1$	0.72	0.80	0.97	0.83
BC$_1$	0.83	0.46	0.89	0.73
BC$_1$	0.71	0.58	0.86	0.72
BC$_1$	0.86	0.34	0.83	0.68
BC$_1$	0.81	0.52	0.69	0.67
Mean	0.86	0.75	0.89	

Table 4.1: R^2 for each base color and participant of the TCSFs measured in Experiment 2

$\eta^2 = .74$), but not for *Modulation Direction* ($F_{2,3} = 0.15$; $p = .925$; $\eta^2 = .07$). Specifically, slope got shallower from BC_1 to BC_{15} in a linear fashion (see Figure 4.5). A linear regression exploring this effect was significant but small ($\beta = 0.004$, $p < .001$) with an R^2 of 0.30. Furthermore, there was a marginally significant interaction of *Base Color* and *Modulation Direction* ($F_{2,42} = 1.53$; $p = .051$; $\eta^2 = .43$), but this interaction was also very complex and difficult to interpret.

To understand the main effects of *Base Color* on the *Intercept* and *Slope* better, the intercepts and slopes were analyzed for base colors in LMS space. A visual inspection of the intercepts and slopes as a function of the L-, M-, S-, cone activations indicated a logarithmic relationship with the S-cone activations, which were then log-transformed for further analysis. Table 4.2 shows the Pearson correlation coefficient for *Intercept* and *Slope*, and the L-, M-, and log-transformed

S-cone activations. It can be seen that *Intercept* most strongly correlates with the log-S-activations (Pearson's r = .33; p < .001) and the *Slope* with the L-activations (Pearson's r = .55; p <.001). These findings suggest that the main effects of *Base Color* on *Intercept* and *Slope* are driven mainly by the log-S- and L-cone activations, respectively, for each base color.

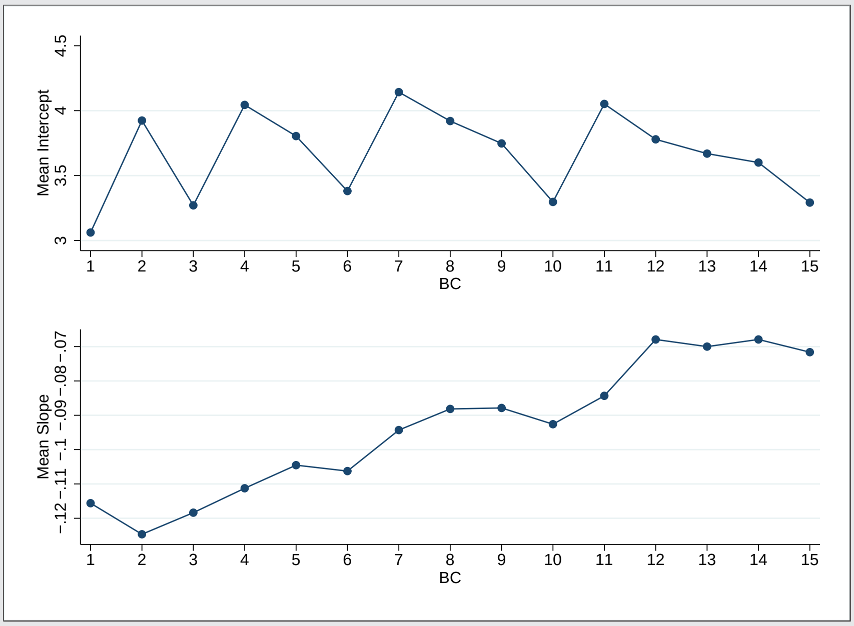


Figure 4.5: *Intercept* (**top**) and *Slope* (**bottom**) as a function of *Base Color* for the TCSFs measured in *Experiment 2*

	Intercept	Slope
L	.09	$.55^{***}$
M	$.22^{***}$	$-.30^{***}$
log-S	$.33^{***}$	$.30^{***}$

$^{*}p < .05$ $^{**}p < .01$ $^{***}p < .001$

Table 4.2: Correlations (Pearson's r) between the L-, M-, and log-transformed S- cone activations and the Intercept and Slope of the TCSFs measured in Experiment 2

4.3 Experiment 3

In this Experiment, detection thresholds were measured for a subset of four base colors, corresponding to the base colors with the largest between-subject variance in lumiance ratios (i.e. BC_{7}, BC_{13}, BC_{14}, and BC_{15}). Furthermore, in contrast to *Experiment 2*, for each participant the same average luminance ratios obtained from *Experiment 1* (see Table 4.3) were used to adjust the luminance of the flicker stimulus modulations. To examine the effect of using average luminance ratios on the TCSFs, the log-transformed contrast sensitivities measured in *Experiment 2* were compared with the log-transformed contrast sensitivities measured in *Experiment 3*. Note that in order to enable a meaningful comparison, for this analysis contrast sensitivities averaged between starting amplitudes were used.

	Modulation Direction			
Base Color	0°	45°	90°	135°
BC_{7}	1.0134	0.9779	0.9619	0.9693
BC_{13}	0.9608	0.9515	0.9692	0.9999
BC_{14}	0.9477	0.9540	0.9825	1.0129
BC_{15}	0.9382	0.9471	0.9858	1.0267

Table 4.3: Average luminance ratios used in Experiment 3

Figure 4.6 shows the contrast sensitivities from both experiments plotted against each other. The sensitivities deviate from a perfect linear relationship with a root mean squared error of 0.29. A four-way repeated-measures ANOVA with the within-subject factors *Base Color*, *Modulation Direction*, *Frequency*, and *Experiment* shows no significant main effect of *Experiment* ($F_{2,1} = 0.84$; $p = .46$; $\eta^2 = .29$) and only one significant interaction effect between *Experiment* and any of the other factors, namely between *Experiment* and *Modulation Direction* ($F_{2,3} = 2.82$; $p = .04$; $\eta^2 = .05$). Subsequent post-hoc tests show that this interaction was mainly driven by a significant difference of Direction 135° and Direction 45° in *Experiment 2* (t-test (2.78 vs. 2.98): $t = 4.01$; $p = .001$) but not in *Experiment 3* (t-test (2.82 vs. 2.93): t

= 2.38; $p = .11$), and a significant difference between *Experiment 2* and *Experiment 3* for 90° (t-test (2.13 vs. 1.99): $t = -3.09$; $p < .01$) but not for any other direction.

Since the difference between contrast sensitivities could have been affected by the magnitude of the difference between the luminance ratios, pairwise t-tests were performed for contrast sensitivities where the absolute difference in luminance ratios was larger than 0.02, for each participant separately. The results show no significant effect of *Experiment* on contrast sensitivity for high luminance ratio differences for any of the participants (all $p > .09$). Similarly, a linear regression of the differences in contrast sensitivities and differences in luminance ratios was not significant ($F_{1,142} = 2.38$; $p = .12$; $R^2 = .02$), indicating that the differences in contrast sensitivities cannot be explained by the differences in luminance ratios.

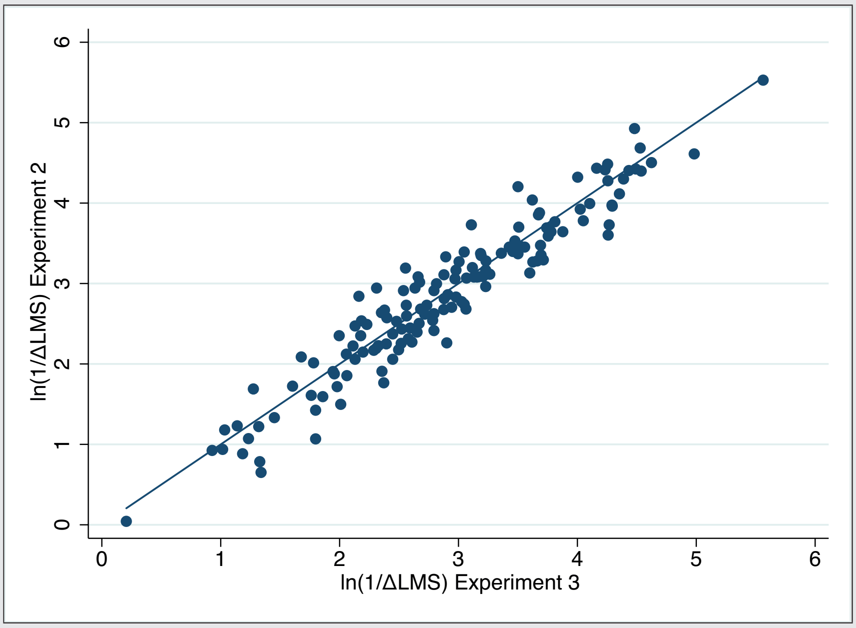


Figure 4.6: The visibility thresholds from *Experiment 2* plotted against the visibility thresholds from *Experiment 3*

Discussion and Conclusion

The aim of this study was to further explore the effect of different base colors on the TCSFs and to investigate inter-individual variance in adjustment for isoluminance in order to test whether the efficiency of the experimental paradigm could be improved by using average instead of individual isoluminance functions. Therefore, first the luminance ratios were measured in *Experiment 1*, then the TCSFs for a wide range of isoluminant stimuli were examined in *Experiment 2*, and finally the contrast sensitivities for individual luminance ratios from *Experiment 2* were compared to the contrast sensitivities obtained for average luminance ratios in *Experiment 3*.

The results of *Experiment 1* indicate that luminance ratios deviated more from a ratio of one, for base colors with higher L- and S- cone activations, in order to minimize luminance flicker. The results of *Experiment 2* show that the TCSFs can be modelled with an exponential function. Interestingly, the intercepts and slopes of the TCSF correlate with the L- and S-cone activations for base color. The results of *Experiment 3* indicate that when using luminance ratios averaged across participants for base colors with a high between-subject variance in luminance ratio, the measured contrast sensitivities are not significantly different from the contrast sensitivities obtained with individual luminance ratios during *Experiment 2*.

In the following, first the results of the present study are discussed on the basis of previous literature. Then limitations of this study are examined.

5.1 Discussion of Results

5.1.1 Modelling the TCSFs for Chromatic Flicker

The main purpose of the present study was to measure the TCSFs for chromatic flicker for a wide range of base colors, based on the experimental paradigm of Bueno Perez et al. (2017). Previous research on flicker perception has shown that the human visual system resolves luminance and chromatic flicker separately (e.g. Shady et al., 2004). Specifically, the TCSFs of chromatic flicker are characterized by low-pass shape that can be sufficiently described by an exponential model (e.g. Dobkins et al., 1997). Bueno Perez et al. (2017) found that the TCSFs can be described by an exponential model for isoluminant stimuli over nine base colors specified in the CIE 1976 UCS diagram, using seven flicker frequencies. In the present study efforts were made to measure TCSFs for an even wider range of base colors covering a large space in the 1967 CIE UCS diagram. In order to increase the time efficiency of the experiment, contrast sensitivities were only measured for three frequencies.

In line with previous studies, the results of *Experiment 2* show that for most conditions an exponential model (linear on a log-scale) generally resulted in a high goodness-of-fit. However, for BC_{12} to BC_{15} the average R^2 were around or below 0.70. This was mainly driven by one participant who reached significantly lower R^2 in these conditions than the other two participants. As discussed later on, this effect might have been attributable to visual fatigue (see section 5.2: Discussion of Limitations). In general, TCSFs with low goodness-of-fits were characterized by large differences in the measured detection thresholds for the two starting amplitudes and/or contrast sensitivities that were higher for 8 Hz compared to 2 Hz. Interestingly, for some conditions this was the case for detection thresholds that were similar for both starting amplitudes, ruling out inaccuracy of the measurement. This band-pass shape is typically a characteristic of the TCSFs for luminance flicker (Swanson et al., 1987), suggesting that for some conditions residual luminance flicker may have been present (cf. Kim et al., 2013; Lou, 2016; Shady et al., 2004). This may have been due to inaccurate luminance ratios that did not fully correct for isoluminant stimuli. What is especially striking is that these effects are most prominent for base colors in the extreme red and blue region of the CIE 1976 UCS color space (i.e., BC_{12}-BC_{15}). This is in line with the observed effects of base color on the luminance ratios (see discussion of *Experiment 1* below), and with findings of Bueno Perez et al. (2017) reporting difficulties in visibility threshold adjustment for base colors in this region of the color space. An explanation for residual luminance flicker for these chromaticities may be that brightness (i.e. luminance) is mainly coded by the L- and M-cones in the visual system (Ripamonti, Woo, Crowther, and Stockman, 2009). Additionally, it was found that for an excitation of L- and M-cones above a certain criterion level, the S-cones contribute to the luminance input (Ripamonti et al., 2009). Thus for base colors with high L-cone activations sensitivity for luminance flicker may be higher, with additional contribution of the S-cones. Moreover, this effect is likely to be influenced by individual differences in L:M cone ratios, that have been shown to vary considerably between subjects (Danilova, Chan, and Mollon, 2013), and which could explain the observed differences between participants.

In their study, Bueno Perez et al. (2017) reported that TCSFs cannot be described by a single function, but depend on base color and modulation direction, and differ between subjects. The results of the present study show similar effects. That is, a main effect of base color was found for the slopes of the TCSFs, while main effects for both base color and modulation direction were found for the intercepts. Specifically, the TCSFs got more shallow towards base color BC_{15} (i.e. towards base colors in the blue and red region of the CIE 1976 UCS color space). Furthermore, the curves were generally higher for base colors with higher S-cone activations. Also the curves were highest for Direction 0° and lowest for Direction 90°, and Direction 45° and Direction 135° being very similar. Additionally, there were significant individual differences throughout the analysis. An important implication of these results is that due to this complex relationship of TCSFs and base colors, no generalizations can be made from experiments that only investigated stimuli that activate a part of the visual system (e.g. red-green flicker).

5.1.2 Individual Variation in Luminance Ratios and Improving the Efficiency of the Experimental Paradigm

The second purpose of the present study was to test whether the efficiency of the experimental paradigm can be improved by using an average isolumiance function compared to individual isoluminance functions per participant. In previous chromatic flicker studies, TCSFs with a decrease in sensitivity for low frequencies were found. It has been argued that this band-pass characteristic could be explained by stimuli not being equal in brightness, resulting in visible luminance flicker (Kim et al., 2013). Thus, in order to adjust the chromatic flicker stimuli for isoluminance, individual isoluminance ratios have to be measured. Since this additional measure drastically increases the required time for chromatic flicker studies (Bueno Perez et al., 2017), efforts have been made in this study to measure inter-individual variance in luminance ratios and to test whether average luminance ratios can be used to measure the TCSFs for chromatic flicker.

As expected, the results of *Experiment 1* indicate that overall there was a substantial variation in luminance ratios between participants. This is in line with previous research showing large inter-individual differences for several functions of the human visual system (e.g. Perz et al., 2014; Perz et al., 2017; Stockman and Sharpe, 2000). Interestingly, the results show that the luminance ratios and their variation between participants were different for different base colors and modulation directions. Specifically, it could be observed that luminance ratios decreased (relative to to a ratio of one) for base colors with higher L- and S-cone activations, while inter-individual variance increased. This suggests that the CIE 1924 $V(\lambda)$ luminous efficiency function needs to be adjusted more for base colors in the short and long wavelength spectrum, which is consistent with the inaccuracies of $V(\lambda)$, especially for short wavelengths, highlighted in the previous literature (Kim et al., 2013; Sharpe et al., 2005). Moreover, an increase in variance for these base colors indicates that individuals differences may be more pronounced for the L- and S-cone sensitivity compared to the M-cone sensitivity. In order to investigate this effect further, the $D(\lambda)$ function was calculated for each participant, which reflects for each wavelength how the the (relative) luminance needed to be adjusted for isoluminance (Bueno Perez et al., 2017). To analyze which cones were adjusted the most by the luminance ratios and to compare the D(λ) between participants, the D(λ) was normalized by the unadjusted spectral distribution of the flicker stimuli to obtain the adjustment ratios for each L-, M-, and S-cone activations individually. Given the observed tendencies in luminance ratios discussed before, we expected the L- and S-cone adjustment ratios to be higher than the M-cone adjustment ratio. However, the results show that only the adjustment ratio for the S-cones was slightly higher relative to the L- and M-cone ratios, although not statistically significant. Given these slightly inconsistent results, further research is needed to investigate the effect of different cone type sensitivities on the adjustment of chromatic flicker stimuli for isoluminance. Moreover, the observed interaction effect of base color and direction on the luminance ratios needs further investigation. While opposite patterns of $\Delta\ M$ and ΔS can be observed for Direction 0° and Direction 135°, they do not fully explain this interaction effect. It would be interesting for future studies to explore this relation in more detail.

In *Experiment 3* the detection thresholds for chromatic flicker were measured with luminance ratios obtained from *Experiment 1*, averaged across participants for each condition. Since the standard deviation of luminance ratios differed significantly for different base colors, only the base colors with the highest variation in luminance ratio across participants were tested. Previous research on TCSFs for periodic luminance flicker and the stroboscopic effect has shown that despite inter-individual variation, TCSFs can be accurately modeled using average visibility thresholds (Perz et al., 2014; Perz et al., 2017). Similarly, we explored whether this also holds for luminance ratios. Indeed, the results show no significant difference between the visibility thresholds measured in *Experiment 2* (using individual luminance ratios) and the thresholds measured in *Experiment 3* (using average luminance ratios). Although the difference was not significant, absolute differences were present. However, there was no effect of the size of the difference between the luminance ratios used in *Experiment 2* and the ratios used in *Experiment 3* on the size of the difference between the measured visibility thresholds. This means that even for luminance ratios that were similar between both experiments the thresholds measured in *Experiment 2* could not be accurately replicated in *Experiment*

3. Contrary to the findings of Kong et al (2018), these results indicate that participants may not be consistent across several measurements when using the method of adjustment. Nevertheless, the results suggest that using an average isoluminance function are sufficient to measure chromatic flicker for a large number of participants, especially if the accuracy of the models is of less importance. This is advantageous since the efficiency of time-consuming chromatic flicker experiments could be increased substantially. Note however, that due to the small number of participants, this effect should be verified in future studies using a larger number of participants and base colors.

5.2 Discussion of Limitations

The presented study has several limitations that have to be acknowledged. Specifically, limitations concern the equipment and the methodology that was used, and confounding factors that may have been present. In the following these limitations are discussed and recommendations for future studies are given.

5.2.1 Limitations of Equipment

An important limitation was that due to the gamut of the system many colors could not be included. That is, the system was not able to produce all colors defined in the CIE 1976 UCS color space but was limited to a subset of the color space. Specifically, colors in the green region of the color space could not be displayed by the system. The base colors were therefore chosen to cover as much of the possible color space that could be displayed. With more advanced LED cube systems, TCSFs for more base colors could be examined.

5.2.2 Limitations of Methodology

In order to increase the efficiency of the experimental paradigm method of adjustment was used. Previous research has found this a reliable and efficient method to measure visibility thresholds for chromatic flicker (Kong et al., 2018). However, the results of *Experiment 3* indicate that method of adjustment may not be as reliable as assumed. Given the consistent results of Bueno Perez et al. (2017), it could be that in order to produce results that are consistent over repeated measurements with the method of adjustment, a specific protocol needs to be followed. Furthermore, the method of adjustment may be more susceptible to confounding factors such as fatigue.

Another limitation to the method of adjustment used in *Experiment 2* is that only the amplitude was adjusted, whereas the frequency values remained constant at three fixed values. Therefore the TCSFs were constructed as an interpolation of these three fixed values. From previous research it was expected that TCSFs can be modelled as an exponential function (Bueno Perez et al., 2017). However, in order to confirm this model, it should be examined whether different result can be obtained when participants adjust the frequency at fixed amplitude values.

In this study special care was taken to minimize confounding effects of luminance flicker using HFP. Previous research has shown HFP to be an effective method to create isoluminant stimuli (van der Horst and Bouman, 1969; Kim et al., 2013). For this method of HFP to be reliable, however, an optimal modulation frequency needs to be chosen. In this study a frequency of 25 Hz was chosen based on previous research (Bueno Perez et al. 2017), whereas in other research frequencies around 10 and 20 Hz were used (Lee, Martin, and Valberg, 1988), corresponding to frequencies where the sensitivity to luminance flicker is higher. Since it is generally very difficult to select the right frequency for HFP, this might have introduced some residual flicker that could not be adjusted for in *Experiment 1* and thus may have caused the bandpass characteristics observed for some conditions in *Experiment 2*.

5.2.3 Confounding Factors

Apart from limitations of equipment and methodology, also confounding factors have to be considered. First, as already earlier mentioned in the discussion, mental and/or visual fatigue may have affected the measurements. Specifically, participants noted that they felt significant fatigue and eye strain during *Experiment*

2, despite the scheduled breaks between measurement blocks. Since the base colors were not counterbalanced between participants and were presented in successive order from $BC_1$to BC_{15}, increasing fatigue may have caused inaccuracies in the measurement for later base colors. For optimal results, it would be advisable to distribute the experiment session over several days and present conditions in a counterbalanced order. In case of *Experiment 2* this would entail that for a total of 8 sessions, a maximum of two sessions (roughly one hour) each day would be recommended. However, a major downside of this would be a considerable decrease in time efficiency and impracticality for participants to come back for several sessions.

Another confounding factor in this study may have been chromatic adaptation. According to Fairchild and Reniff (Fairchild and Reniff, 1995) there are two phases of adaptation n accelerated adaptation of a few seconds, and a slower adaptation of roughly one minute. At a constant luminance the chromatic adaptation was found to be 90% complete after roughly one minute. In the present study an adaptation time of two minutes was used for each base color. While two minutes should thus be enough time to adapt to a base color, individual differences or a lack of attention to the stimulus during the adaptation time may have influenced the results of this study. Furthermore, it can be hypothesized that chromatic adaptation might even occur during the flicker presentation. However, to our knowledge no studies have yet investigated this effect.

Additionally, also flicker adaptation might have been present. In this study the contrast sensitivity thresholds were analysed as a function of frequency to obtain the TCSFs for each condition. The resulting TCSFs, however, might be sensitive to flicker adaptation. Specifically, Shady et al. (2004) found that the visibility of chromatic flicker at higher frequencies depends on the adaptation status. That is, without flicker adaptation, the slope of TCSFs decreased more rapidly, with a CFF at 20 Hz, compared to the TCSFs when adapted, with visible flicker beyond 30 Hz. This phenomenon may also explain the results found during the frequency selection procedure (see section 2.2.1: Frequency Selection). As described before, initially a set of four frequencies (i.e. 2 Hz, 8 Hz, 15 Hz, and 25 Hz) was chosen to model the TCSFs. In order to provide insight into the range of frequencies where chromatic flicker could be observed a pilot study was conducted. Based on previous research it was expected that for the majority of base colors chromatic flicker could be created with frequencies up to and higher than 25 Hz (Bueno Perez et al., 2017). However, the results of the pilot study showed that for some of the selected base colors chromatic flicker was not visible for a frequency of 25 Hz. While this effect may be partly explained by the findings of Shady et al (Shady et al., 2004), the fact that visibility depended on the displayed condition further complicates the interpretation. It would be interesting for further research to investigate chromatic flicker adaptation for stimuli of different chromaticities.

Appendices

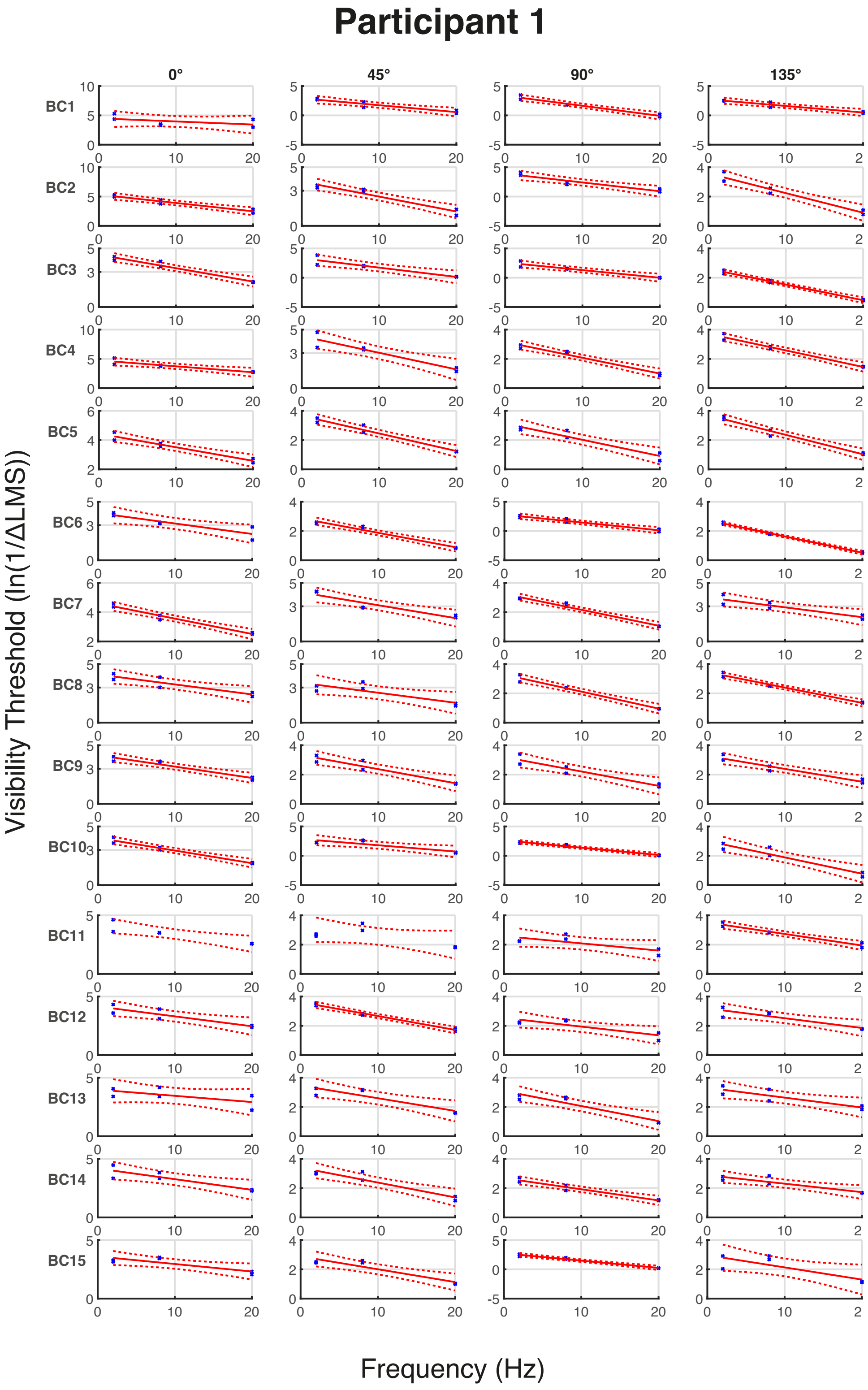
Appendix A Mean and Standard Deviation of Luminance Ratios

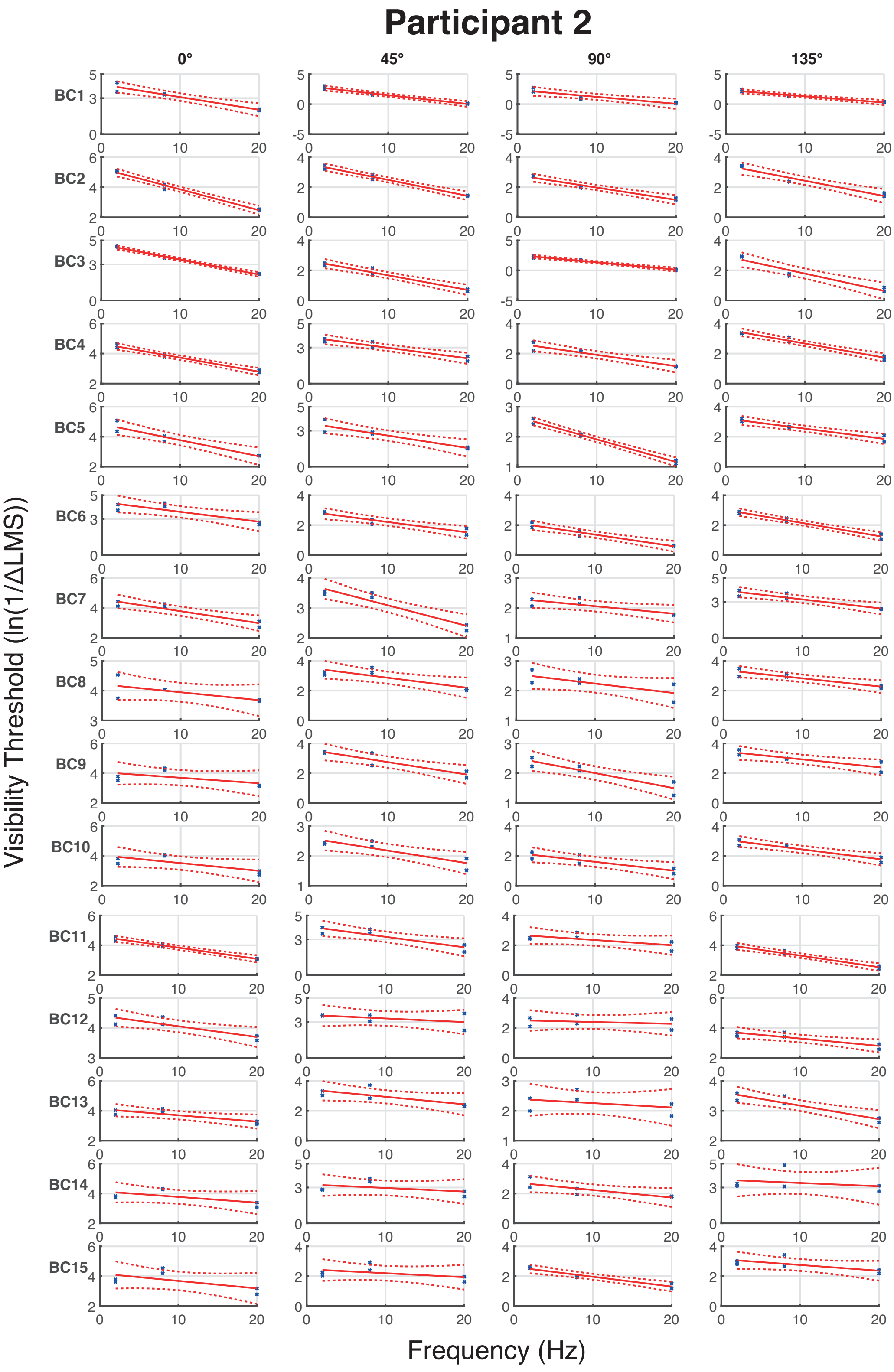
	Modulation Direction							
	0°		45°		90°		135°	
Base Color	M	SD	M	SD	M	SD	M	SD
BC$_1$	1.02	0.03	1.00	0.02	0.99	0.01	0.98	0.02
BC$_2$	1.01	0.02	0.99	0.03	0.98	0.01	0.97	0.01
BC$_3$	1.01	0.02	0.99	0.03	0.98	0.01	0.98	0.02
BC$_4$	1.01	0.02	0.99	0.02	0.97	0.02	0.97	0.02
BC$_5$	1.00	0.02	0.98	0.02	0.98	0.02	0.99	0.02
BC$_6$	0.98	0.02	0.97	0.02	0.98	0.02	1.00	0.02
BC$_7$	1.01	0.03	0.98	0.03	0.96	0.01	0.97	0.02
BC$_8$	0.99	0.02	0.97	0.02	0.97	0.02	0.98	0.01
BC$_9$	0.98	0.02	0.96	0.02	0.97	0.02	1.00	0.01
BC$_{10}$	0.96	0.02	0.96	0.02	0.98	0.01	1.01	0.02
BC$_{11}$	0.99	0.03	0.97	0.03	0.95	0.01	0.97	0.02
BC$_{12}$	0.98	0.03	0.95	0.02	0.96	0.01	0.99	0.02
BC$_{13}$	0.96	0.03	0.95	0.03	0.97	0.01	1.00	0.03
BC$_{14}$	0.95	0.03	0.95	0.03	0.98	0.02	1.01	0.02
BC$_{15}$	0.94	0.03	0.95	0.02	0.99	0.02	1.03	0.03

M = mean, SD = standard deviation

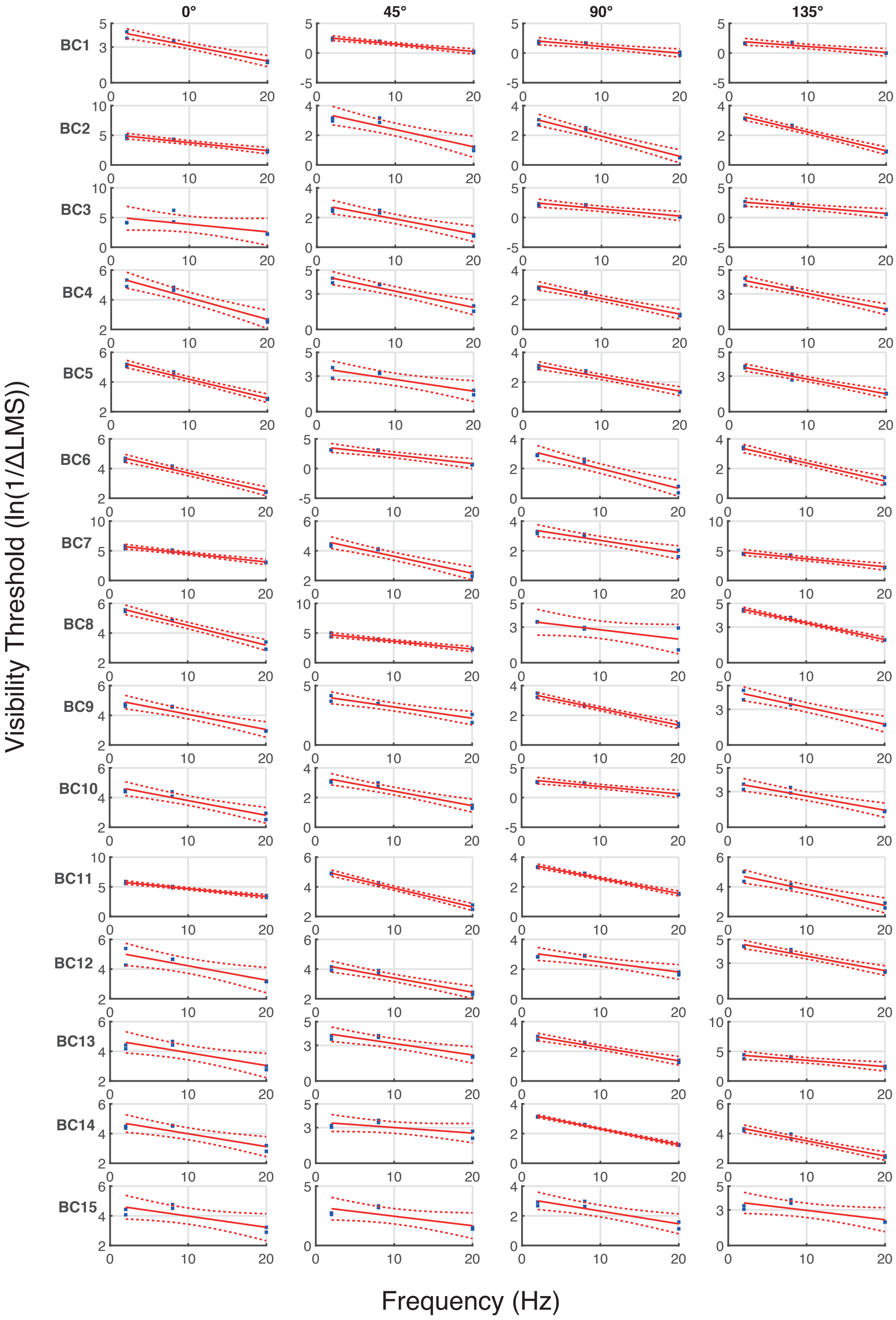
Mean and standard deviation of luminance ratios for *Base Color* and *Modulation Direction* averaged across participants

Appendix B TCSFs from Experiment 2




Participant 2
0°
45°
90°
135°
BC1
BC2
BC3
BC4
BC5
BC6
BC7
BC8
BC9
BC10
BC11
BC12
BC13
BC14
BC15
Visibility Threshold (ln(1/ΔLMS))
Frequency (Hz)
0
10
20

Participant 3



Appendix C Information and Consent Form

Technische Universiteit
Eindhoven
University of Technology

Informed consent form

This document gives you information about the study *Measuring the Temporal Chromatic Contrast Sensitivity Function: An Extended Paradigm.* Before the study begins, it is important that you learn about the procedure followed in this study and that you give your informed consent for voluntary participation. Please read this document carefully.

Aim and benefit of the study

The aim of this study is to measure the between-subject variance of the luminance adjusting function. The data is used to build a model that describes the temporal chromatic contrast sensitivity function of chromatic flicker.

This study is performed by R.M. Spieringhs, S.L. Hartmeyer, P. Wijsen, students under the supervision of I. Vogels, and X. Kong of the Human-Technology Interaction group.

Procedure

In the experiment, you will evaluate luminance flicker stimuli for different base colors. Since the study is about color, the Ishihara test for color deficiency will be carried out first. Then the tasks are as follows:

Before the experiment you will receive a short training session to familiarize you with the experiment setup and the adjustment task. During the training session, demo stimuli will be shown and you have to follow the instructions of the experimenter.

During the experiment, two alternating colors with different luminance will be shown. Your task is to iteratively adjust the luminance ratio between the two colors to find the point of minimum flicker. You can use the four arrow keys on the keyboard to change the luminance ratio: The *Up-arrow* key to increase the ratio with large steps; the *Down-arrow* key to decrease the ratio with large steps; the *Right-arrow* key to increase the ratio with small steps; the *Left-arrow* key to decrease the ratio with small steps. When you think the flicker phenomenon is minimal, you can press the *Ente*r key to continue to the next trial.

Risks

This study does involve risks for people who are overly sensitive to light, are susceptible to migraine, and have a history of epilepsy. Therefore, we ask that you do NOT participate in this study if the above applies to you! There are no other risks or detrimental side effects.

Duration

This study will last approximately 2 hours in total. The experiment will be divided into two one-hour (with 20 minutes' experiment, followed by 20 minutes' rest and another 20 minutes' experiment) sessions.

Participant's paraph ____

Participants

You were selected because you agreed to participate the experiment after being contacted through the JFS Participant database.

Voluntary

Your participation is completely voluntary. You can refuse to participate without giving any reasons and you can stop your participation at any time during the study. You can also withdraw your permission to use your data up to 24 hours after the study is finished. All this will have no negative consequences whatsoever.

Compensation

You will be paid 10 euros per hour (€2.00 extra if you do not study or work at the TU/e or Fontys Eindhoven).

Confidentiality

All research conducted at the Human-Technology Interaction Group adheres to the Code of Ethics of the NIP (Nederlands Instituut voor Psychologen – Dutch Institute for Psychologists).

We will not be sharing personal information about you to anyone outside of the research team. No video or audio recordings are made that could identify you. The information that we collect from this study is used for writing scientific publications and will only be reported at group level. It will be completely anonymous and it cannot be traced back to you.

Further information

If you wish to receive more information about this study you can contact R.M. Spieringhs, S.L. Hartmeyer or P. Wijsen (contact email: r.m.spieringhs@student.tue.nl, s.l.hartmeyer@student.tue.nl, p.p.wijsen@student.tue.nl).

If you have any complaints about this study, please contact the supervisors, I. Vogels, (I.M.L.C.Vogels@tue.nl) or X. Kong (x.kong@tue.nl).

Certificate of Consent

I, (NAME)……………………………………….. have read and understood this consent form and have been given the opportunity to ask questions. I agree to voluntarily participate in this study carried out by the research group Human Technology Interaction of the Eindhoven University of Technology.

________________________________ ________________________

Participant's Signature Date

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