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A simple and cost effective colorimeter for characterising observer variability in colour matching experiments

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Abstract

In colour science, colour matching functions (CMFs) are essential for measuring how sensitive the human eye is to various light wavelengths and determining the colour of stimuli in various viewing situations. It has traditionally taken a lot of time and effort to conduct colour-matching studies to describe an observer's perception of colour. This article presents a simple and compact 3D-printed colorimeter designed to conduct colour-matching experiments. A pilot study was conducted using the colorimeter with four observers participating in a maximum saturation-type colour matching experiment., where they would match spectral lights in the 400-720 nm range to three narrow band LED primaries. The study aimed to assess the accuracy and performance of the system in measuring individual observer CMFs. Results showed that the CMFs of the four observers showed normal characteristics of a colour-normal observer. However, the limited number of measurements per observer may have contributed to the lack of smoothness in the CMFs. The CMFs of one of the observers were compared with Stiles and Burch 1955 RGB CMFs, after normalising to the same primaries. We noted that the red and green functions fell within the expected range, while the blue function showed some unusual characteristics. The limitations of the colorimeter and overall pilot study were also discussed. In conclusion, the colorimeter showed promising results in measuring CMFs, however the limitations need to be addressed to improve matching accuracy. Additionally, further measurements are required to better characterise intra-observer and inter-observer variabilities.

Introduction

Colour matching functions (CMFs) are essential in colour science as they provide a quantitative description of the way humans perceive colours. CMFs are a set of three functions that quantify the sensitivity of the human eye to different wavelengths of light, and they play a vital role in defining the colour of stimuli under different viewing conditions. Accurate measurement of CMFs is crucial for a wide range of applications, including colorimetry, photometry, colour reproduction, colour management and material appearance.

Historically, performing colour matching experiments to characterise observer's colour perception through the measurement of CMFs have been a lengthy and complex affair [1, 2, 3]. Experimental setups proposed were bulky, comprising several light sources, filters, optical elements, etc, all with the aim to create a bipartite field that allows the comparison of two colour stimuli side by side. Jiaye Li et al. [4] has done an extensive review of noteworthy CMF sets and factors affecting their accuracy such as rod intrusion, breakdown of Grassman's law of additivity and observer metamerism.

The Commission Internationale d'Eclairage (CIE) has collected measured CMFs for a number of observers and averaged these across observers to derive a standardized set of CMFs[5]. Those standard colour-matching functions are designed to represent the mean colour-matching response of the population of human observers with normal colour vision [6]. However, several studies have shown that there are undeniable discrepancies between predicted colour matches using standard CMFs and actual visual matches made by colour-normal observers [7, 8, 9].

In this article, we present the design of a simple and compact 3D printed colorimeter for the purpose of conducting colour matching experiments. A short pilot study was conducted where four observers participated in a colour matching experiment of the maximum saturation type. The aim of the study, was to assess the performance and accuracy of our system in measuring CMFs of individual observers.

Experimental Setup

Design

The experimental setup utilized in this study features a unique 3D printed bipartite field structure for measuring the CMFs of individual observers. The setup consists of a central wedge-shaped structure with an aperture for the viewing field, flanked by detachable integrating hemispheres on each side as shown in Figure 1. The inside of the integrating hemispheres and the wedge-shaped structure were painted with several layers of a white Barium Sulphate coating to create a diffuse and lambertian surface. The left hemisphere serves as the integrating chamber for the matching field and contains a single input socket for an RGB LED light engine that acts as the primaries for the matching task. The right hemisphere functions as the integrating chamber for the test field and contains two input sockets, one for a narrowband monochromatic test stimulus and the other for the same RGB LED light engine as the matching field, which in this case acts as a desaturation component. Additionally, a diffusing film was placed in front of the output aperture such that it was in contact with the edge of the wedge structure. As a result, two homogeneous half fields with a sharp separation in between was created, which would be the bipartite field as shown in Figure 2. The RGB LED light engine was designed to house four LEDs in close proximity, two red, one green and one blue. The peak wavelengths for the red, green, and blue LEDs are 634 nm, 534 nm, and 452 nm, respectively. These primaries were selected based on commercially available high power LEDs that had peak wavelengths in the vicinity of the Stiles and Burch 1955 RGB primaries[1].

The LED light engine was powered by a TLC59711 PWM LED Driver from Adafruit, which can control 12 channels of 16-bit PWM output independently. Only six of those channels were used, three for the matching side LED primary and three for the desaturation side. The driver board was programmed using an Arduino Mega microcontroller. A look-up table was used to map the 65,536 linear levels of the LED driver to 1024 gamma-corrected levels with a correction value of 2. This was done to ensure that the adjustments of LED brightness were smooth and perceptually uniform. A simple control interface was built, con-

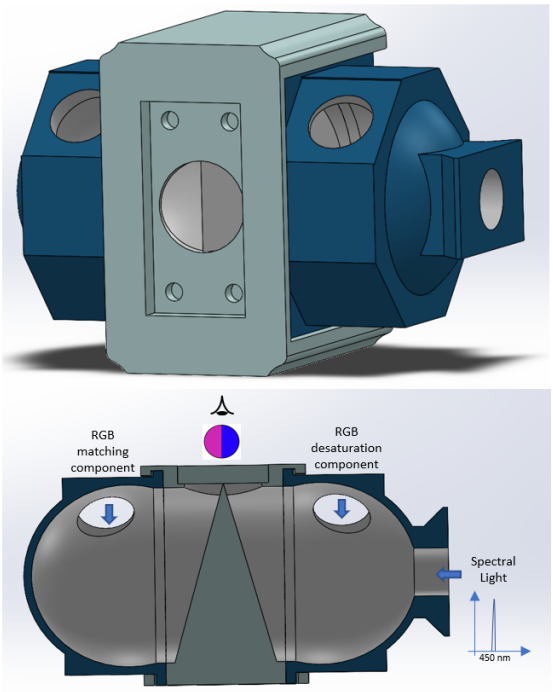

Figure 1. *(a) : 3D design of bipartite field structure, with integrating hemispheres, (b) : Cross-section of the structure as seen from the bottom, showing the integrating chambers and the wedge-shaped feature, forming the bipartite field.*

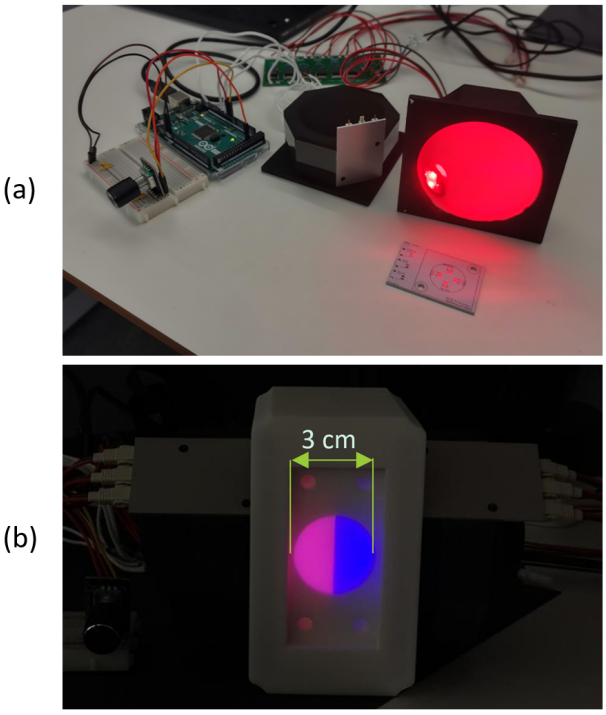

Figure 2. *(a) : Integrating hemispheres containing the RGB LED light engine, (b) : Bipartite field showing test field and matching field side by side for colour matching*

sisting of 3 rotary encoders. Each encoder would control one channel of the primaries. Rotating the encoder clockwise, would increase the intensity of its respective channel on the matching side. Rotating the encoder counter-clockwise, would decrease the intensity of its channel primary on the matching side if it is active, else it would start increasing the intensity of the channel primary on the desaturation side. This ensured that the same primary could not be active on both the matching side and the desaturation side. Additionally, a toggle switching between coarse and fine adjustments and a reset button were also integrated into the system.

The setup allowed for precise control and calibration of the spectral power distribution of the stimuli, and the bipartite field structure ensures accurate measurement of CMFs. The test stimulus were spectral lights, with peak wavelengths ranging from 400 to 720 nm at 10 nm intervals, generated from a monochromator (Bentham TMc300). A Xenon lamp (Bentham Il7 Xenon source) was used as input to the monochromator. The output slit of the monochromator was adjusted such that spectral lights had a FWHM of around 9 nm. To control for the viewing field, the bipartite field, which had a diameter of 3 cm, was placed at a distance of more than 100 cm from the observer, which corresponds to a viewing field of roughly 1.6°.

Calibration

Different parts of the system were calibrated. The spectral power density of the primaries were measured at half of their maximum intensity and recorded, as shown in Figure 3. From these measurements, we obtain the column vectors for **R**, **G** and **B** used in Eq. (1), to be used later. The chromaticity shifts in the primaries as their intensities are increased from 10% to 100% at every 10% interval were characterised. The average shift for each primary in terms of Δu and Δv are tabulated in Table 1.

The largest chromaticity shift measured was in the green primary, where it is still less than 1% shift from the actual chromaticity of the green primary. We thus consider chromaticity shifts to be negligible.

Table 1 : Chromaticity shifts in the R,G and B primaries

Primaries	Average Δu	Average Δv
Red	0.00023	0.00003
Green	0.00107	0.00017
Blue	0.00017	0.00047

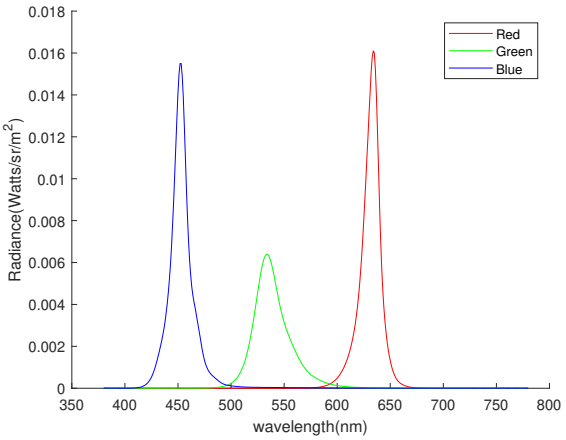

Figure 3. *Spectral power distribution of the primaries at half their max intensities*

Next, the spectral power distributions of the test stimuli

were measured, as plotted in Figure 4. They were then normalised such that they integrated to the same power. These normalised spectral stimuli is what we denote as $\mathbf{S}_{\lambda_i}$ in later sections.

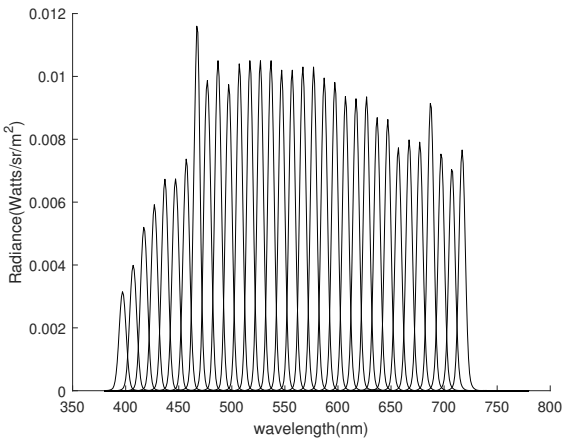

Figure 4. *Spectral power distribution of the spectral stimuli*

Pilot Study

The main objective of this pilot study is to assess the performance of the setup in measuring CMFs and to identify potential limitations of the current design.

Method

The experiment was performed in a dark room, where only the bipartite field would be illuminated. Observers were briefed on the study's objective and given verbal instructions on how to operate the controls of the setup. They were then given time to adapt to the viewing conditions and familiarize themselves with the controls by attempting to match a few test fields. The experiment began with presenting a spectral stimulus to the observer on the test side of the bipartite field, with all primaries turned off. The observer would then scan the bipartite field freely with both eyes, while attempting to match the colour of the test side by adding primary components on the matching side. They were informed that for some test stimuli, they may need to desaturate with one of the primaries if necessary. Observers were instructed to aim for an acceptable match using the coarse control before switching to fine adjustments, and to ignore potential differences due to Maxwell's spot in the center of the bipartite field. After a match was reached, the spectral power distributions of the test field, $\mathbf{T}_{\lambda_i}$, and match field, $\mathbf{M}_{\lambda_i}$, for the test spectral light at λ_i were measured using a spectroradiometer (Konica Minolta CS-2000). $\mathbf{T}_{\lambda_i}$ and $\mathbf{M}_{\lambda_i}$ are 401 by 1 vectors, where the rows represent the power at each unit wavelength between 380 nm to 780 nm. These steps were repeated for all the spectral lights within the 400-720 nm range at every 10 nm interval. Four colour normal observers participated in the pilot study, male age 51 (I), male age 60 (P), male age 39 (M) and male age 62 (J). The experiment was done once per observer.

Results

From the SPD of the test field, $\mathbf{T}_{\lambda_i}$, the spectral stimulus was extracted as $\mathbf{S}_{\lambda_i}$, where λ_i corresponds to the peak wavelengths, from 400 nm to 720 nm, at intervals of 10 nm. It is worth noting that $\mathbf{T}_{\lambda_i}$ and $\mathbf{M}_{\lambda_i}$ were scaled according to the normalisation process done earlier on their respective $\mathbf{S}_{\lambda_i}$.

We have noticed that a small component of the match field is leaked into the test field and vice versa, due to some translucency in the wedge-shaped bipartite field structure. This can be handled if we deal in the difference between test field and match field as shown in the Eq. (2). The matrix $\mathbf{b}$ is a 401 by 1 column vector representing that difference. Since the difference between the test and match field would be a function of the primaries and the spectral light, we can represent matrix $\mathbf{A}$ as shown in Eq. (1), where $\mathbf{R}$, $\mathbf{G}$, $\mathbf{B}$ and $\mathbf{S}_{\lambda_i}$ are 401 by 1 column vectors representing the spectral power distributions of the primaries and the spectral light at peak wavelength λ_i, respectively.

$$\mathbf{A} = \begin{bmatrix} \mathbf{R} & \mathbf{G} & \mathbf{B} & \mathbf{S}_{\lambda_i} \end{bmatrix} \tag{1}$$

$$\mathbf{b} = \mathbf{T}_{\lambda_i} - \mathbf{M}_{\lambda_i} \tag{2}$$

Given matrix $\mathbf{A}$ and $\mathbf{b}$, the coefficients of the primaries that would match the test stimulus can be obtained from Eq. (3).

$$\mathbf{x} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b} \tag{3}$$

Matrix $\mathbf{x}$ would then be a column vector containing the coefficients of the primaries in the first three rows and the coefficient for the spectral light in the final row. The elements of matrix $\mathbf{x}$ are then normalised such that the coefficient of the spectral light, $\mathbf{S}_{\lambda_i}$ is -1. This ensures that the coefficients of the primaries active on the match side of the bipartite field are always positive, while those on the test side are negative. Repeating those steps for all spectral lights, we can obtain the coefficients of the primaries that would match them. Those coefficients can then be plotted against the wavelength range corresponding to λ_i to obtain the CMFs. The computed CMFs based on the colour matching data of the four observers are plotted in Figure 5.

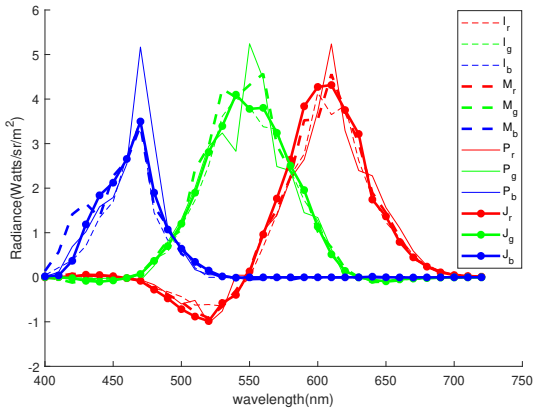

Figure 5. *Computed CMFs of the four observers*

Comparison with Stiles and Burch 1955 RGB CMFs

In order to get a better appreciation of the performance of the colour matching function measurements, it is worth comparing with known CMFs from past experiments. Experimental CMFs derived with a particular primary set can be converted by linear transform to CMFs corresponding to other primaries, such as the CIE X, Y, Z primaries[4]. In this case, we choose to convert our measured CMFs to the ones corresponding to the same primaries used to generate the Stiles & Burch 2-deg CMFs. The latter were based on the measurements from 10 observers and they probably represent the best estimate of the 2-deg CMFs [10].

Only the CMFs of observer J were converted and compared in this preliminary study, because he was the most meticulous observer of the group who took great care in reaching an accurate match. His CMFs were normalised to monochromatic primaries, 645 nm 526 nm and 444 nm, the same ones used in generating the Stiles & Burch 2-deg CMFs. The latter were then plotted alongside the converted CMFs of observer J, as shown in Figure 6.

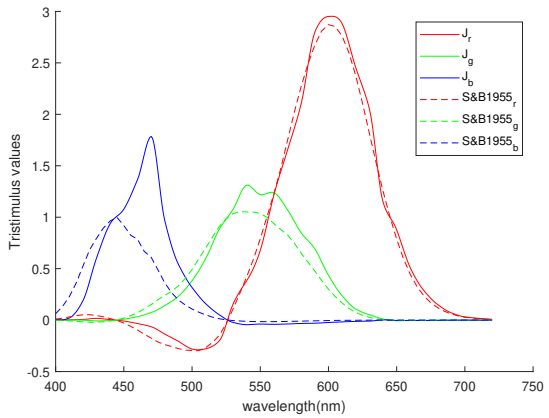

Figure 6. *Comparing observer J's CMFs with the Stiles and Burch 1955 RGB CMFs*

Discussion

From the plotted CMFs in Figure 5, we can observe that the CMFs of the four observers show the normal characteristics of a colour-normal observer, with peaks more or less around the same region and notable negative values for the red primary around the 460 – 540 nm region where significant desaturation would be expected. The magnitude of the peaks and the variations in shape of the CMF curves may be due to observer differences. Nonetheless, significantly more than one set of colour matching measurements per observer would be required to properly distinguish between intra-observer and inter-observer variabilities. The limited number of measurements per observer may also be the reason for the lack of smoothness in the CMFs.

When comparing with the Stiles and Burch 1955 RGB CMFs, in Figure 6, we can observe that the red and green CMFs of observer J more or less falls within the expected range of the corresponding Stiles and Burch CMFs. However, the blue function is significantly different, with an uncharacteristic peak around 470 nm. It is unclear whether this is due to a large matching uncertainty in that region, given that the observer made only one match per spectral stimuli. The transformation to CMFs corresponding to a new set of primaries could also introduce errors, specially if there is significant matching uncertainty at those wavelengths coinciding with the primaries. Also, it is worth noting that all of our four observers reported significant difficulty in matching spectral stimuli in the 460 - 510 nm range. More measurements are definitely required to better characterise the matching uncertainty.

Additionally, there were other limitations with the experimental setup :

- The light intensity was insufficient in the edges of the visible spectrum. In the 400 – 440 nm region, the luminance of the field was below the photopic level (10 cd/m^2). Although we limited our viewing field to less than 2°, which according to Oleari[11], should limit rod intrusion, at such low luminance levels rods may still impact colour matching.
- Our setup did not have a traditional Maxwellian view system which would focus the light from the bipartite field directly onto the retina. As a result, light emanating from the bipartite field was diverging outwards. Since the field is observed at a distance, this limits the amount of retinal illumination significantly, further exacerbating the effect of rod intrusion.
- The bipartite field's edge was not as sharp as desired, and its translucency increased towards the thinner section of the wedge-shaped structure, causing leakage from one integrating chamber to the other.
- Observers reported several physiological phenomena which affected their ability to reach a colour match when doing the experiment, such as, a prismatic effect when wearing high power glasses, the presence of Maxwell spot, afterimages, adaptation to the viewing field reducing their colour discrimination. In many cases, the observers were unable to find a convincing match and settled for colours that were the closest to the test stimulus.

Conclusion and Future works

In this article, we proposed a relatively simple colorimeter for the purpose of measuring CMFs of individual observers. We outlined briefly its design, the calibration process, and a pilot study where the performance of the colorimeter is assessed. From the results, the colorimeter in its current form shows promise in measuring CMFs. However, based on the feedback of observers and on the measured CMFs, it is clear that there are some significant shortcomings. One of the main limitations, is the lack of adequate luminance of spectral stimuli in the edges of the visible spectrum. While we want to keep our system simple in its construction, some optical elements could still be added to improve its ability to gather light and focus it in a more directional way towards the observer's eyes. Additionally, further data processing methods could be explored to reduce the number of colour matches required to get accurate data. Ultimately, if the matches could be made purely from LED sources and not require near-monochromatic stimuli from a monochromator, this would greatly simplify and speed up the process of measuring CMFs, which has historically been a tedious process. In a broader sense, this work represents an iterative step of a bigger project where the goal is to provide a step change in the ability to recover and predict quantities of individual human colour perception, such as to be able to accurately characterise both colour matching functions and colour discrimination thresholds of individual observers.

Acknowledgments

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Author Biography

Luvin Munish Ragoo received his Bachelor in Electrical Engineering and Computer systems from Monash University (2016) and his MSc in Colour Science from University of Eastern Finland (2019). He is currently employed as a PhD candidate at the Norwegian University of Science and Technology. His PhD topic is titled ’Experimental determination of individual variations in colour matching and colour discrimination’, where the goal is to develop an experimental setup to measure the small differences in colour perception of individual observers.

Ivar Farup received his MSc in technical physics from the Norwegian Institute of Technology in 1994 and his PhD in applied mathematics from the University of Oslo, Norway, in 2000. He currently serves as a professor of computer science at the Norwegian University of Science and Technology, mainly focusing on colour science and computational colour image processing.