Colourlab

Measuring individual differences in colour-matching functions

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ICVIO Team

- **Individual Colour Vision based Image Optimisation**
- Norwegian Research Counsil Funded (IKPLUSS), 2020-2024
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- Lab assist: Assoc. Prof. Peter Nussbaum, Dept. Comp. Sc., NTNU

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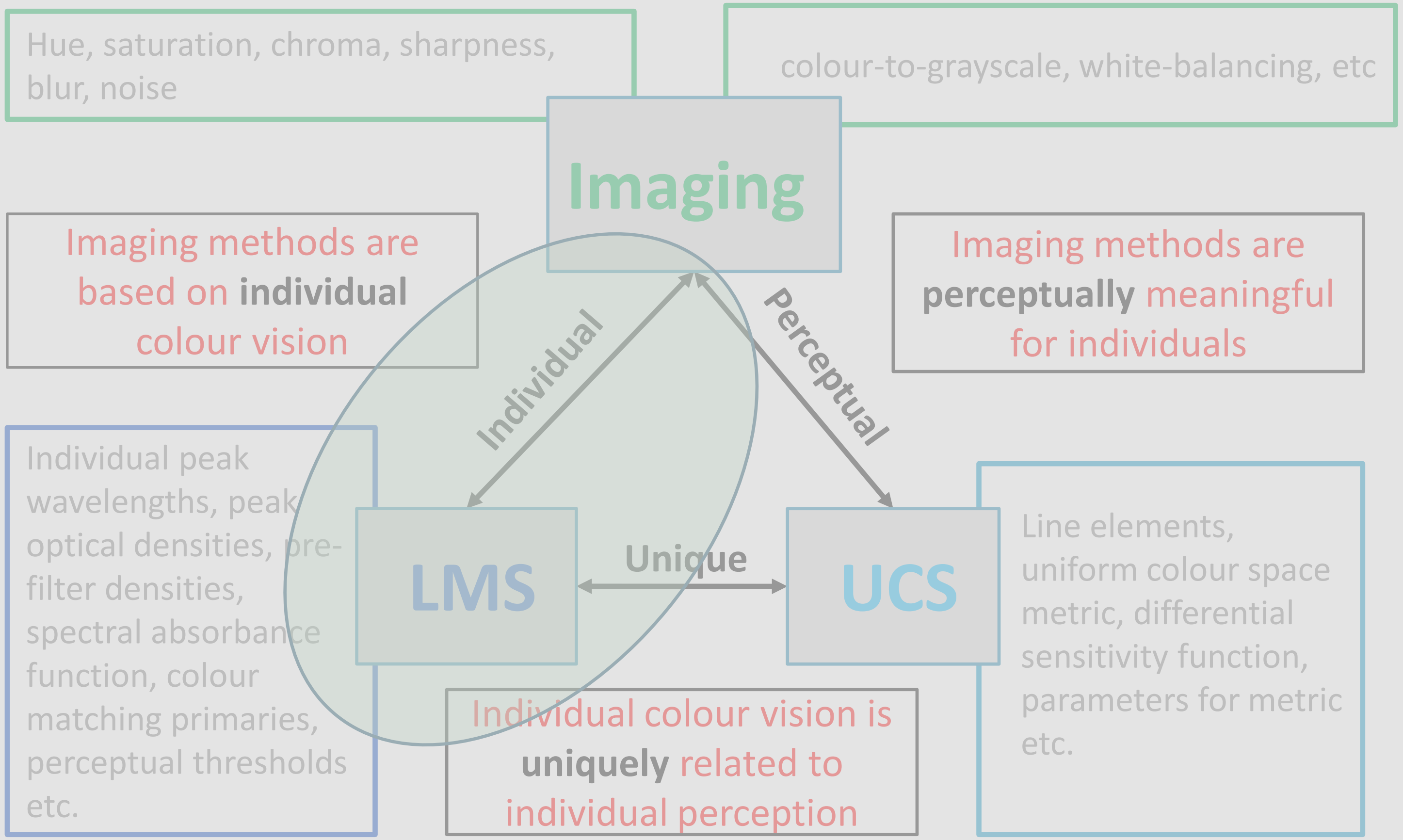

Aims

1. Develop a relatively simple experimental setup for measuring colour-matching functions.
2. Attempt to characterise observer metamerism in terms of their individual observer CMFs.
3. Estimation methods to streamline the process.

Colorimeter Design
First iteration

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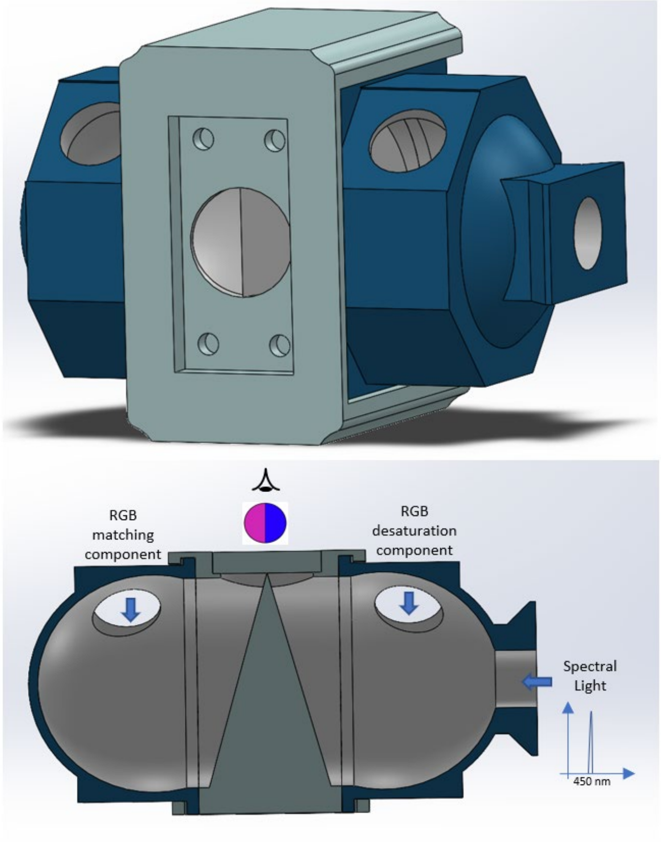
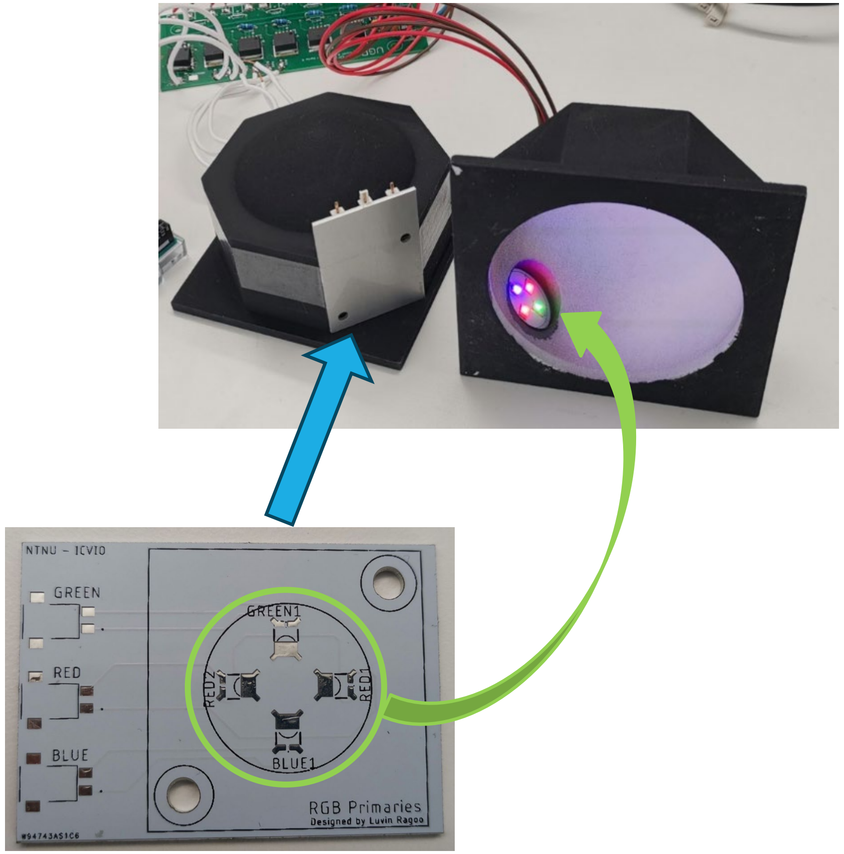
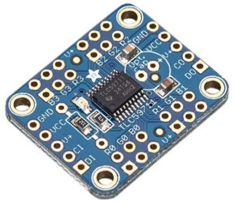
(a)

(b)





RGB LED Light Engine



12-channel 16-bit PWM LED driver

Ragoo, Luvin Munish, and Ivar Farup. "A Simple and Cost Effective Colorimeter for Characterising Observer Variability in Colour Matching Experiments." *London Imaging Meeting*. Vol. 4. Society for Imaging Science and Technology, 2023.

Colorimeter Design
Current iteration

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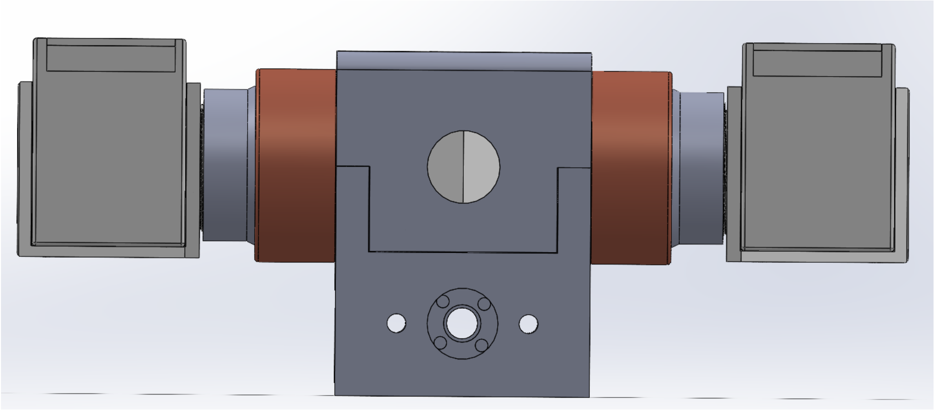
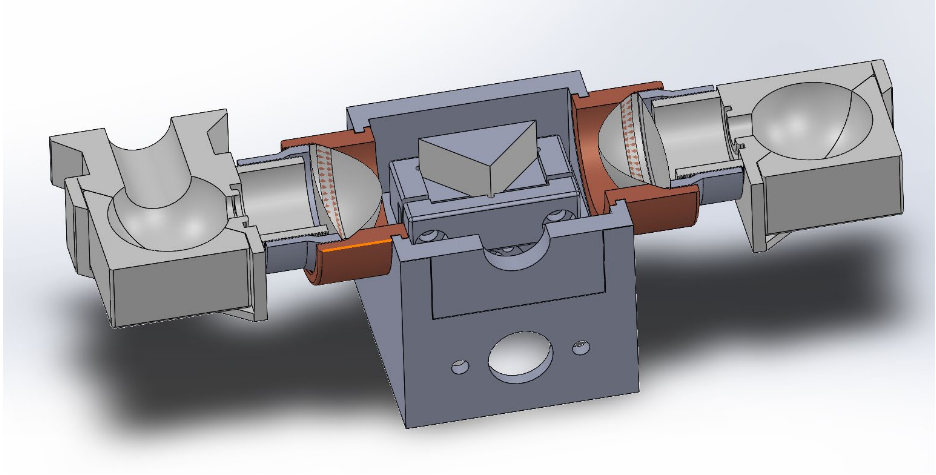
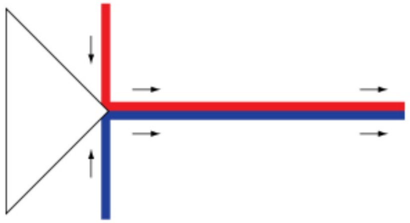




- Reduced the size of the integrating spheres to increase their efficiency.
- Adding collimating lenses to make the field more directional
- Knife-edge mirror to create a sharp bipartite field
- Lenses' positions adjustable such that light exiting the integrating spheres are right at the focal length → parallel rays incidenting on mirror → homogeneous bipartite field



Ragoo, Luvin, Ivar Farup, and Jan Henrik Wold. "Apparatus and Method for Measuring Individual Colour-Matching Functions." (2024).

Colorimeter Design
Current iteration

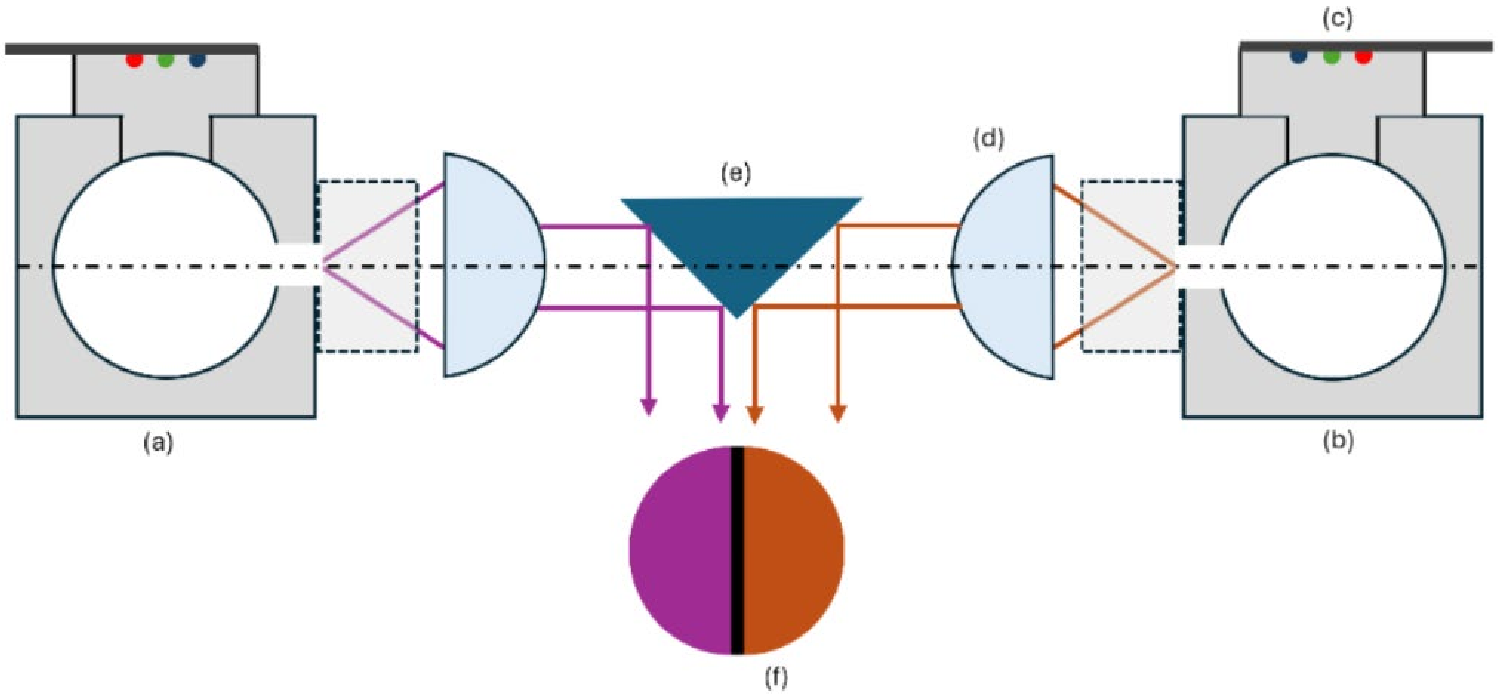
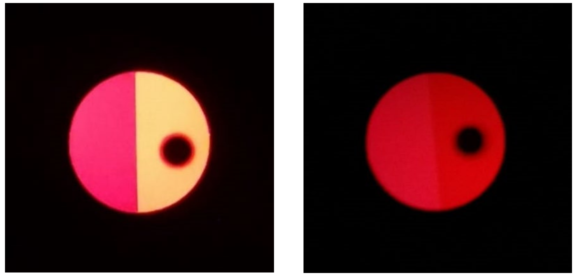
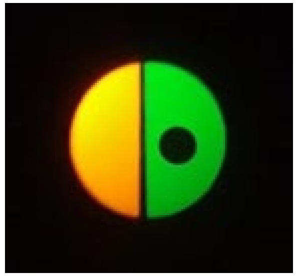


Fig. 1. Schematic diagram of the colorimeter. (a) Integrating chamber for the test field, it has two inputs (not shown on the diagram), the near-monochromatic test stimuli and the LED light engine. (b) The integrating chamber for the match field has only one input for the LED light engine. (c) LED light engine. (d) Aspheric condenser lens. (e) Knife-edge right-angle prism mirror. (f) Resulting bipartite field with adjustable gap width.



No gap



with gap

Ragoo, Luvin, Ivar Farup, and Jan Henrik Wold. "Apparatus and Method for Measuring Individual Colour-Matching Functions." (2024).

Colorimeter Design
Characterisation : Test lights

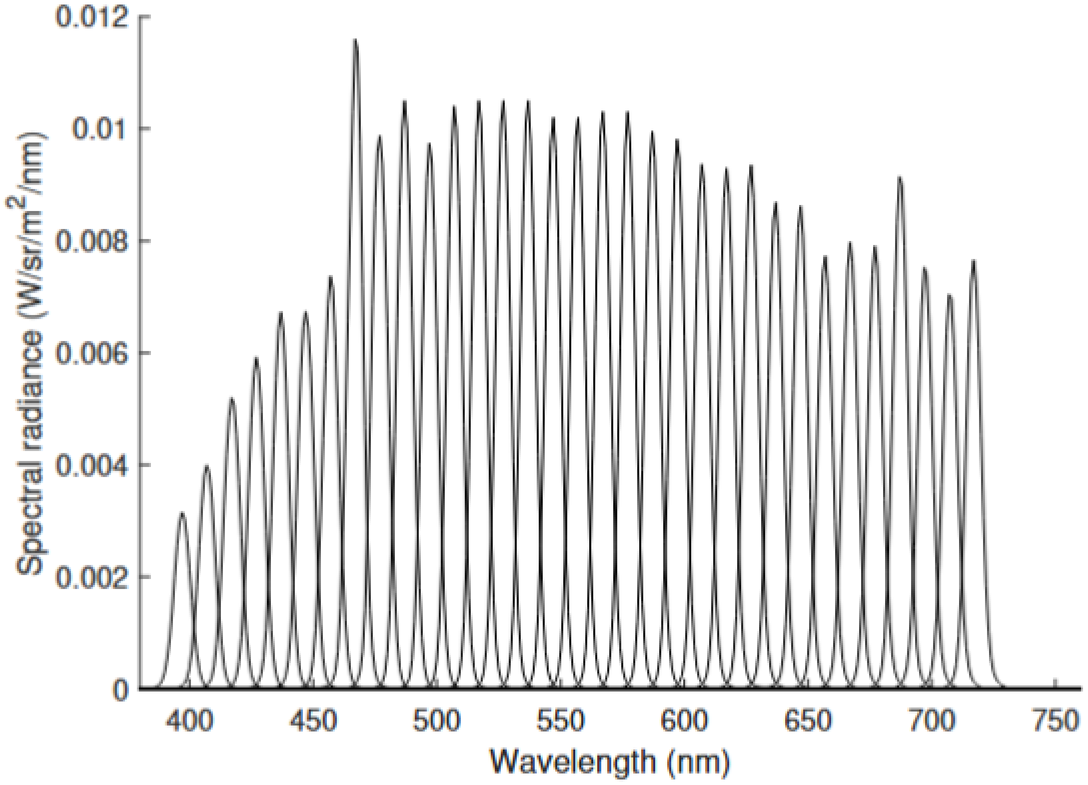


Figure 4. SPDs of the test lights

Ragoo, Luvin, Ivar Farup, and Jan Henrik Wold. "Apparatus and Method for Measuring Individual Colour-Matching Functions." (2024).

Colorimeter Design
Characterisation : RGB LED lights

Colourlab

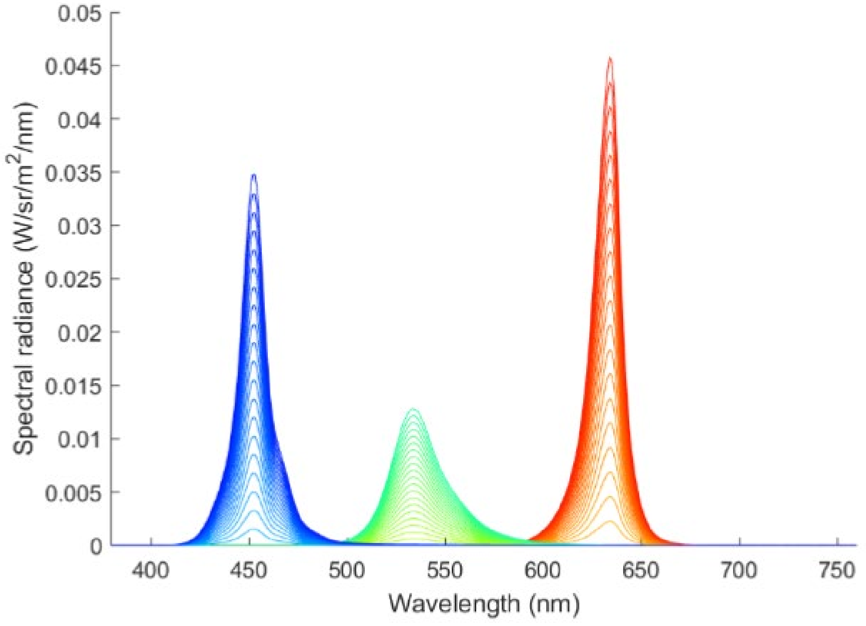


Figure 5. SPDs of the RGB LED lights at every 5 % intensity interval

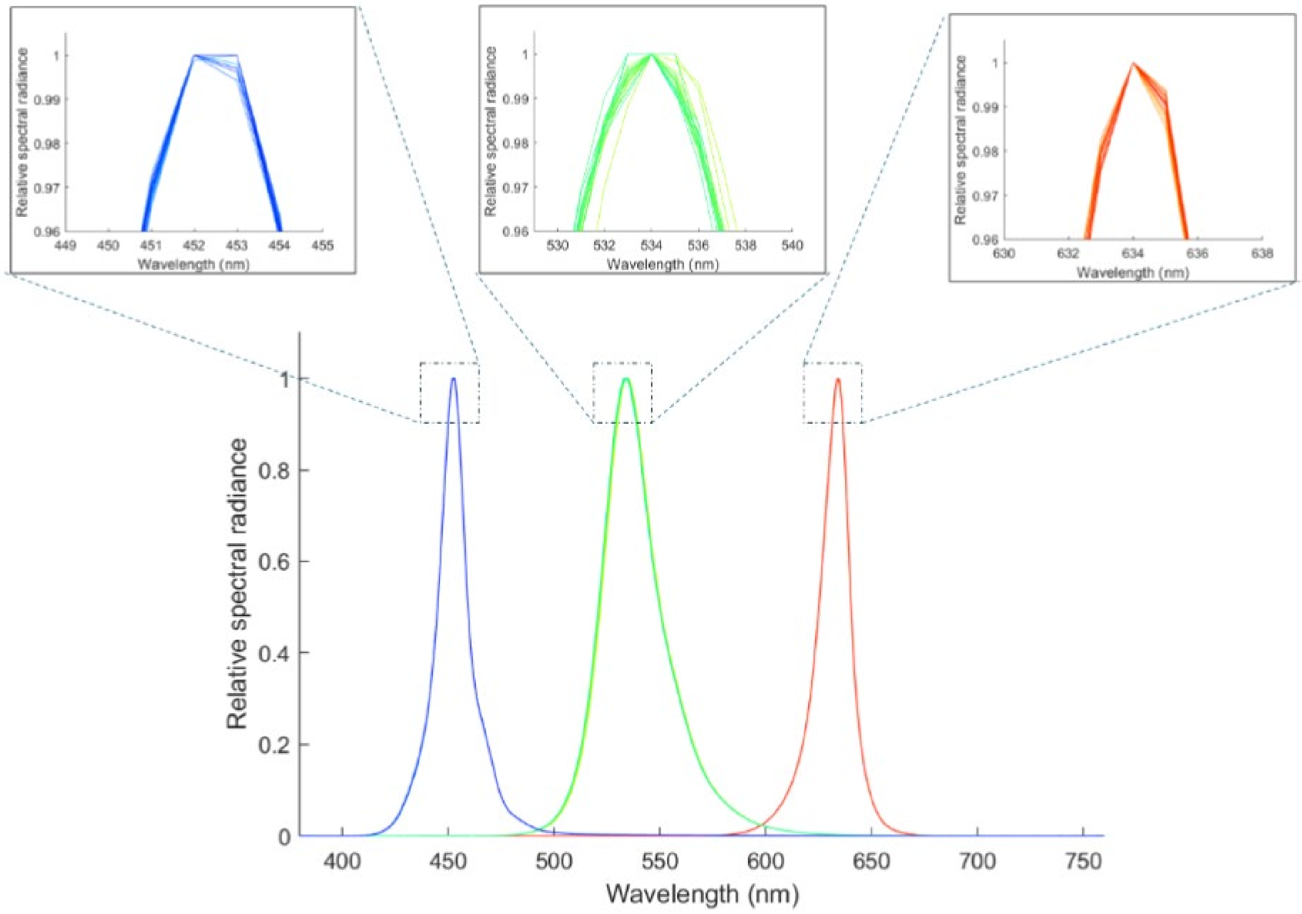


Figure 6. Relative SPDs of the RGB LED lights (normalisation to peak value of 1)

Ragoo, Luvin, Ivar Farup, and Jan Henrik Wold. "Apparatus and Method for Measuring Individual Colour-Matching Functions." (2024).

Colorimeter Design
Characterisation : R, G, B reference stimuli

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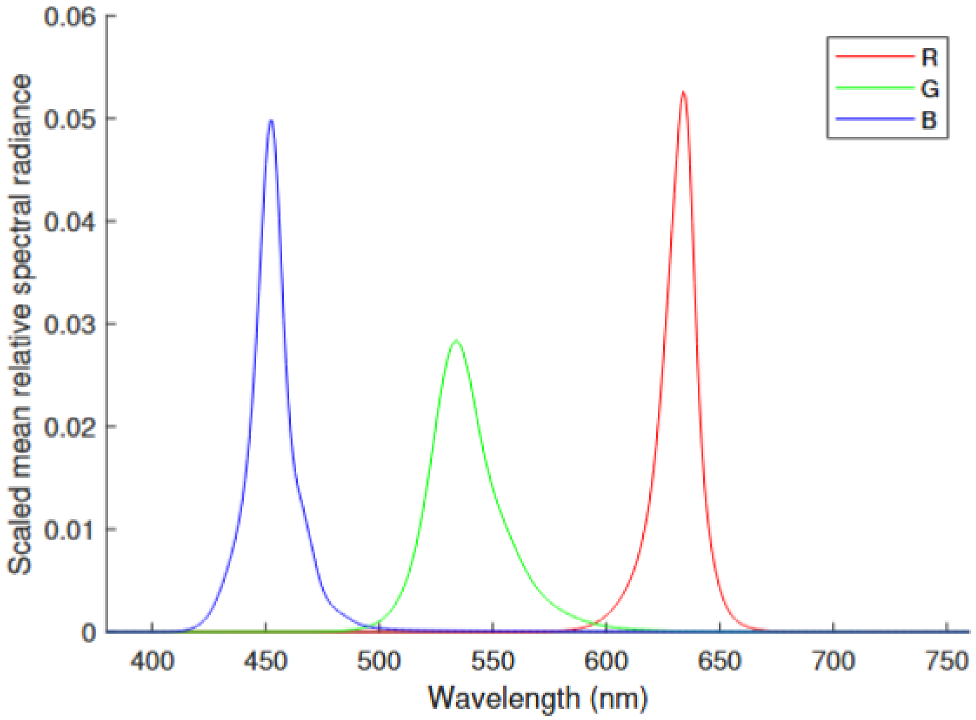
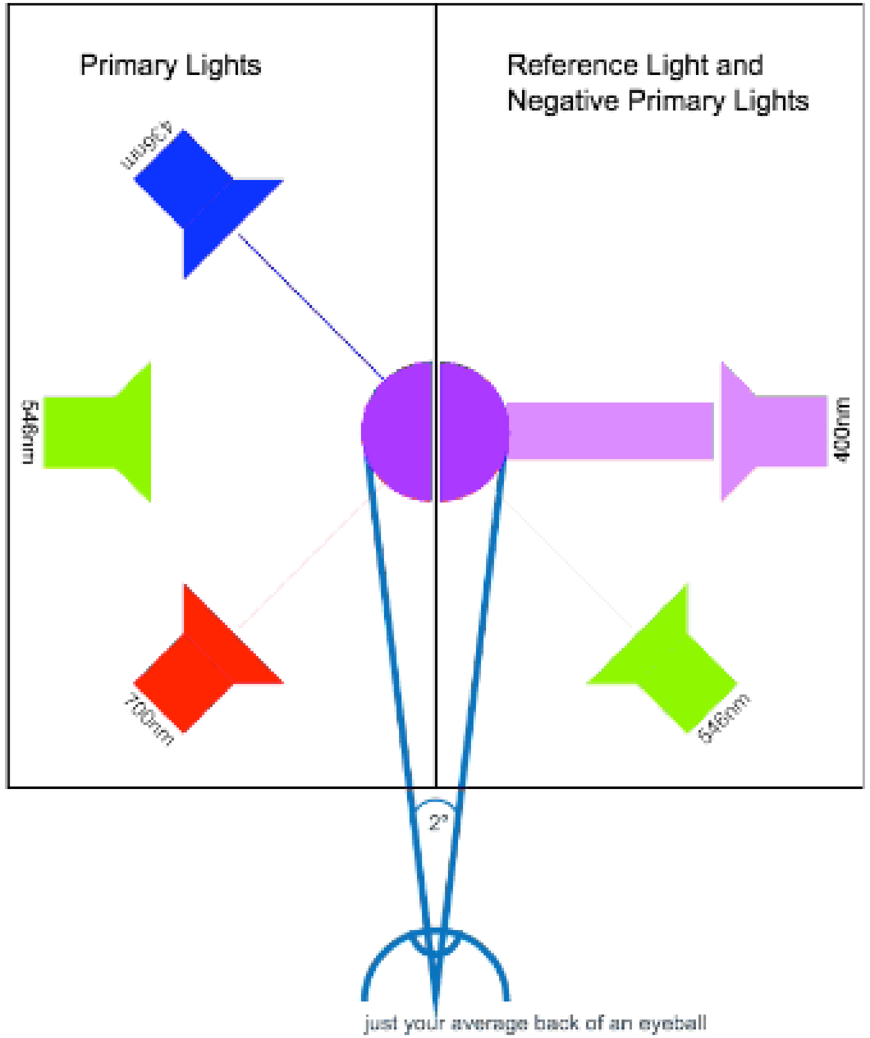
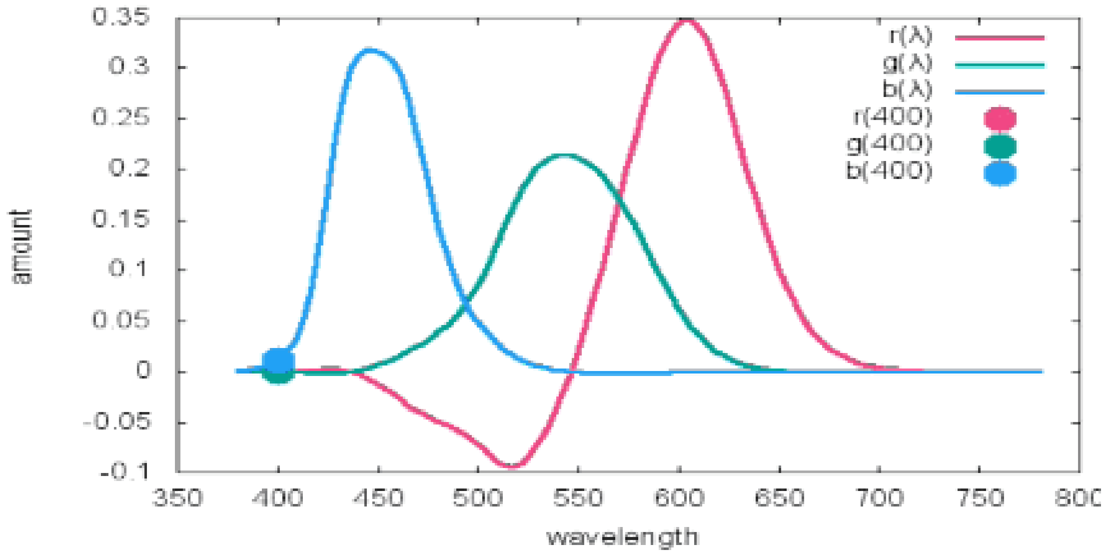


Figure 7. Scaled mean relative SPDs of the RGB LED lights, the scaling making their integrals (i.e. sums of their values at the sampling wavelengths of the spectroradiometer) all equal to 1 (The SPDs define the reference colour stimuli, **R**, **G**, and **B**.)

Ragoo, Luvin, Ivar Farup, and Jan Henrik Wold. "Apparatus and Method for Measuring Individual Colour-Matching Functions." (2024).

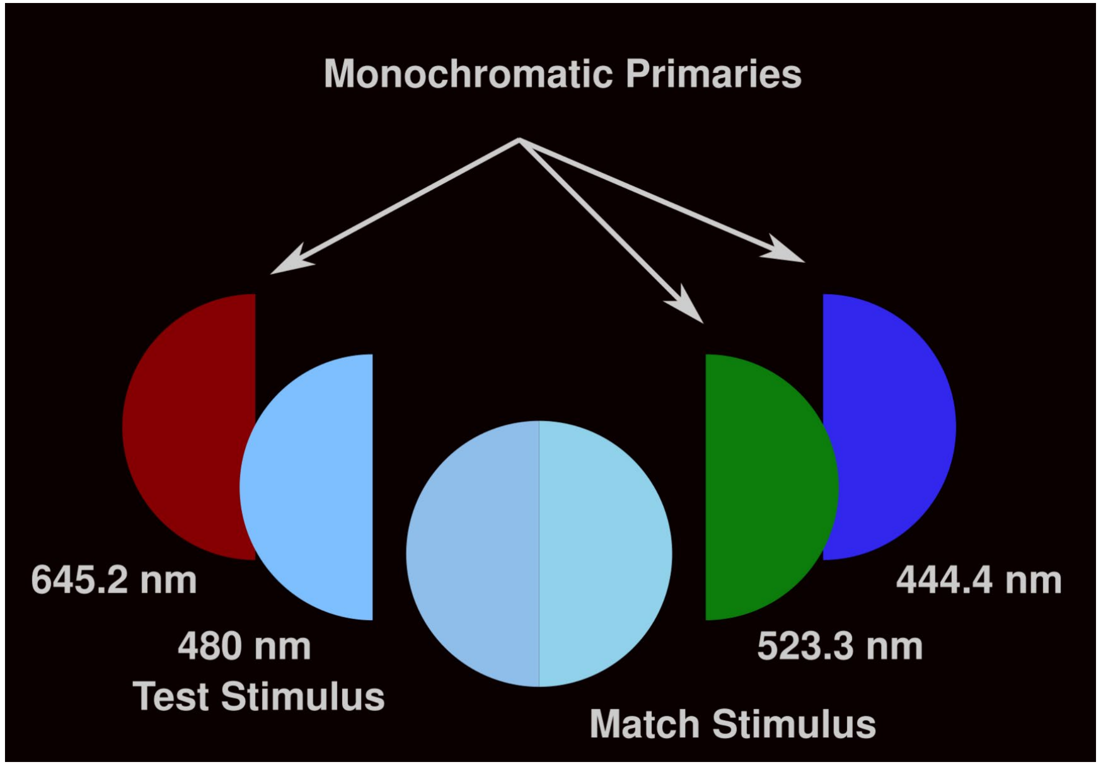
Experiment
Method



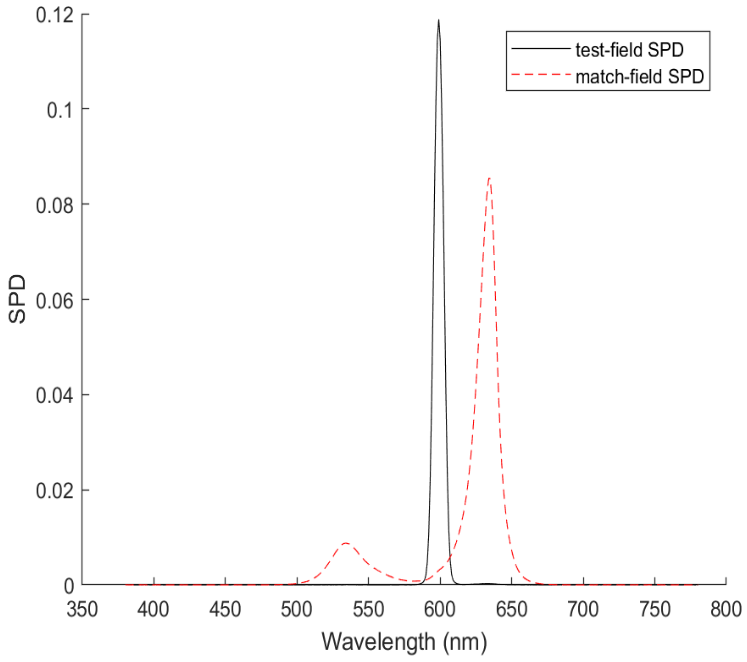


Reference : A Beginner's Guide to (CIE) Colorimetry | by Chandler Abraham | Color and Imaging | Medium

Experiment
Measurement



For example, for a test light of peak wavelength, 600 nm :



Experiment
Computing colour-matching coefficients

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

$$\mathbf{A}_{\lambda_i}\mathbf{x}_{\lambda_i} = \mathbf{b}_{\lambda_i}$$

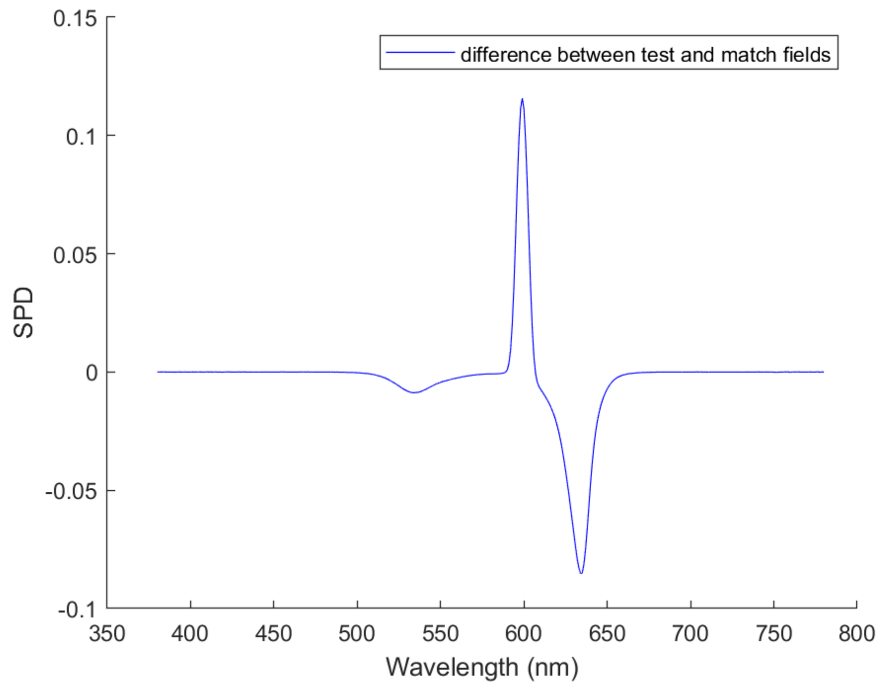
$$\mathbf{b}_{\lambda_i} = \bar{\mathbf{T}}_{\lambda_i} - \bar{\mathbf{M}}_{\lambda_i}$$

$\mathbf{R}, \mathbf{G}, \mathbf{B}$ *and* $\mathbf{S}_{\lambda_i}$ *are 401 by 1 vectors representing the spectral power distribution of the Red, Green, Blue primaries and the spectral light at peak wavelength* λ_i

$\mathbf{b}_{\lambda_i}$ is a 401 by 1 vector representing the difference between the match and test field.

Finally, the coefficients for the primaries that would match a test stimulus with peak wavelength λ_i , can be obtained:

$$\mathbf{x}_{\lambda_i} = (\mathbf{A}_{\lambda_i}^T \mathbf{A}_{\lambda_i})^{-1} \mathbf{A}_{\lambda_i}^T \mathbf{b}_{\lambda_i}$$

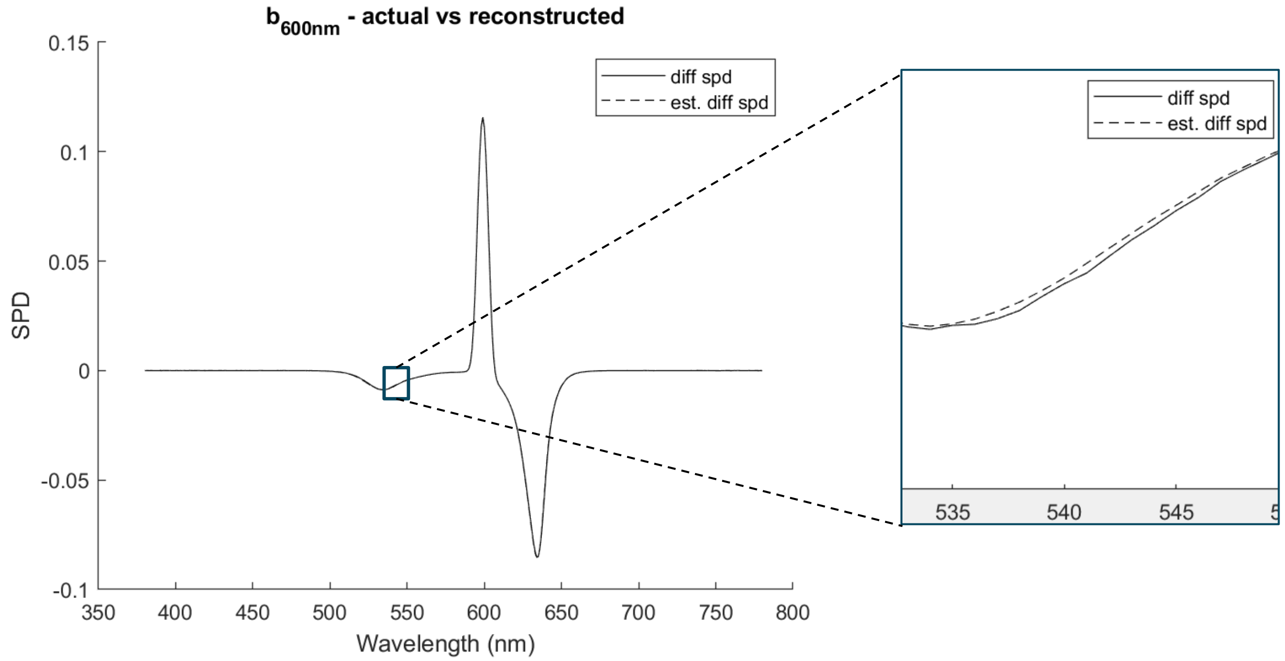


Experiment
Computing PSNR

Assessing estimation accuracy :

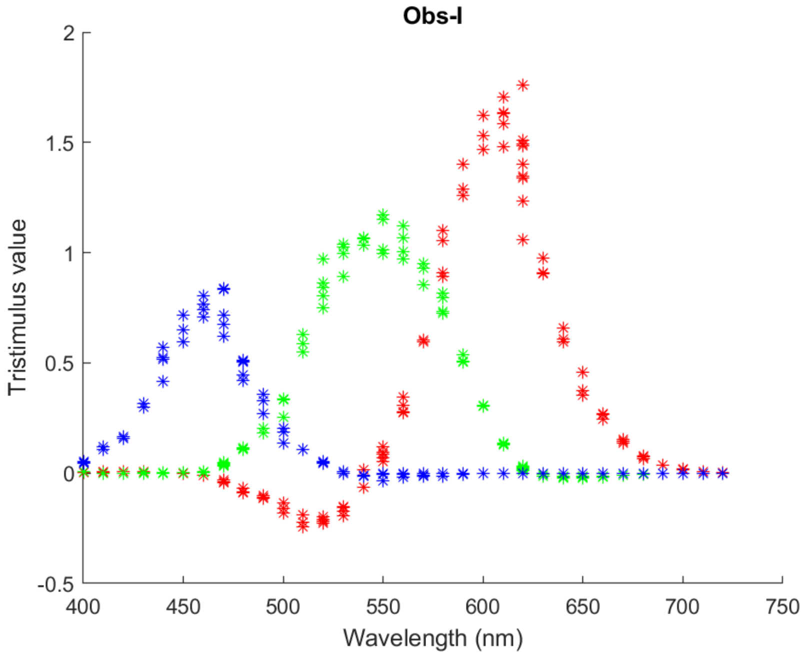
$$\mathrm{PSNR}_{\mathbf{Ax},\lambda_i} = 20\log_{10}\left(\frac{\max(\mathbf{b}_{\lambda_i})}{\mathrm{rmse}(\mathbf{A}_{\lambda_i}\mathbf{x}_{\lambda_i}, \mathbf{b}_{\lambda_i})}\right)$$

(Gives a measure of the stability of the system)

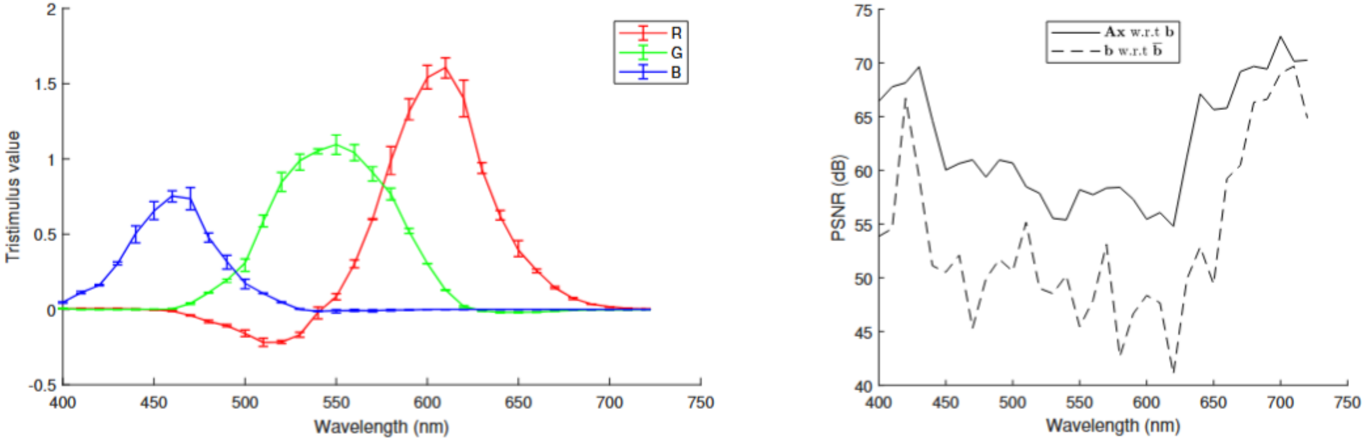


Assessing observer's matching uncertainty :

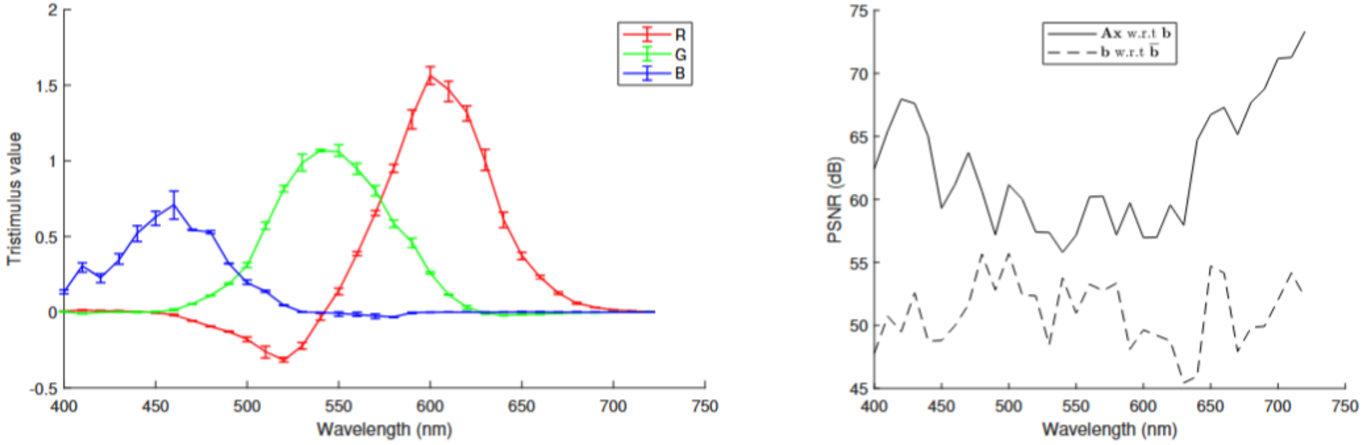
$$\mathrm{PSNR}_{\mathbf{b},\lambda_i} = 20\log_{10}\left(\frac{\max(\overline{\mathbf{b}}_{\lambda_i})}{\mathrm{rmse}(\mathbf{b}_{\lambda_i}, \overline{\mathbf{b}}_{\lambda_i}))}\right)$$



Results
Individual Observer CMFs



Observer I



Observer T

CMF plots (on the left) :

- Mean CMFs are obtained from the average of the computed colour-matching coefficients, plotted at each test wavelength.
- Error bars represent the 95% confidence intervals of the mean colour-matching coefficients (obtained by bootstrapping).

PSNR curves (on the right) :

- Solid curves show the quality of estimation of colour-matching coefficients at each test wavelength.
- Dashed curves show the observers matching uncertainty at each test wavelength.

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Results
Individual Observer CMFs

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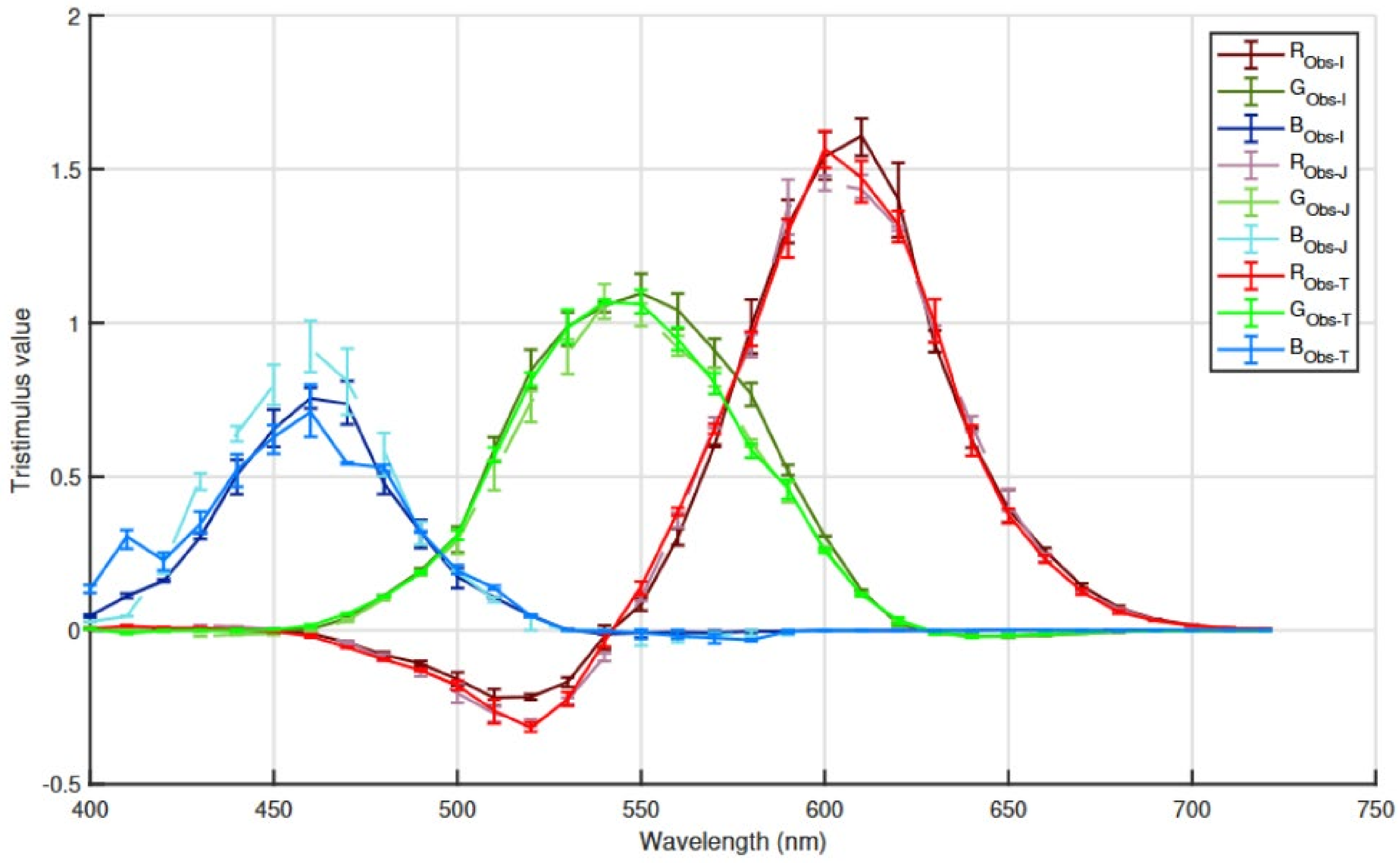

Fig. 11. Comparing the CMFs of three observers for inter-observer differences

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Results
rg-chromaticity diagrams

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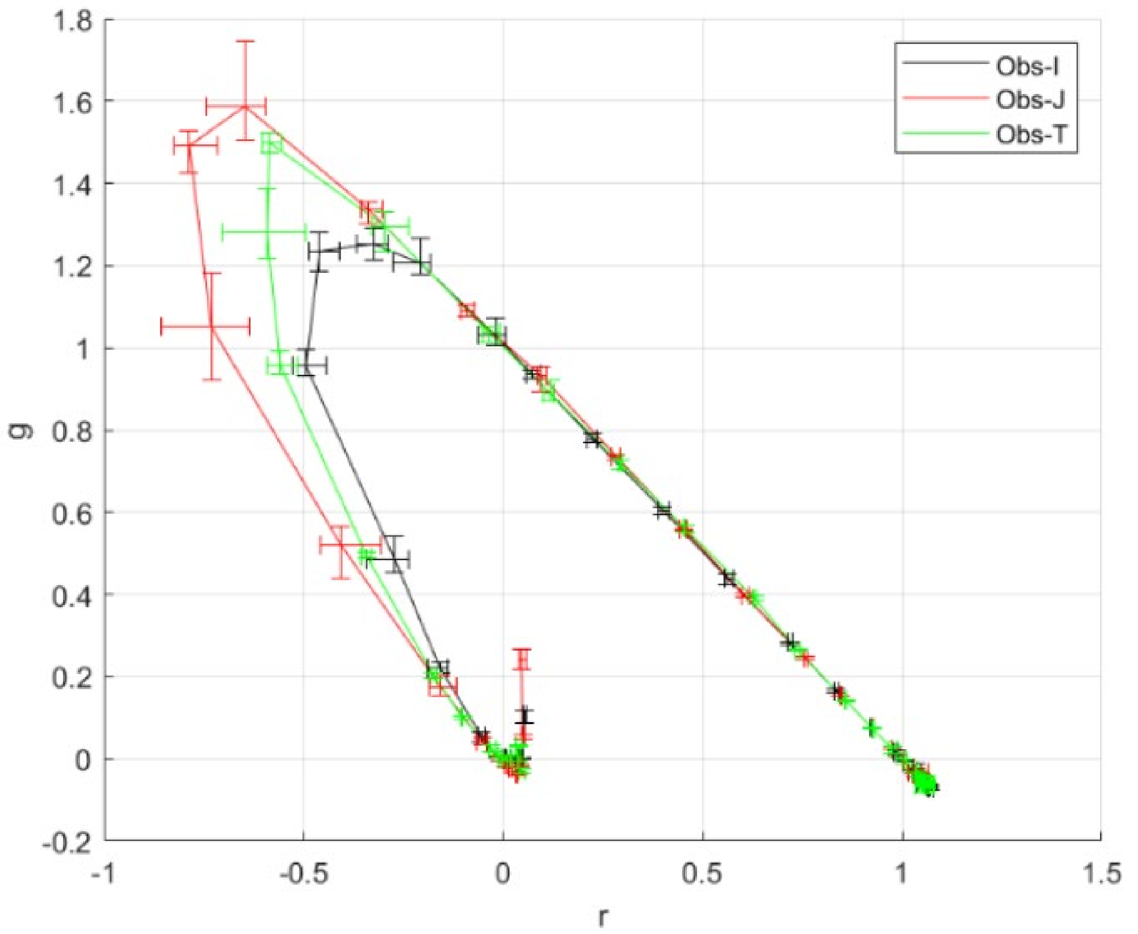

Fig. 12. rg-chromaticity diagrams with error bars of observer I, J and T.

Results
Colorimeter performance

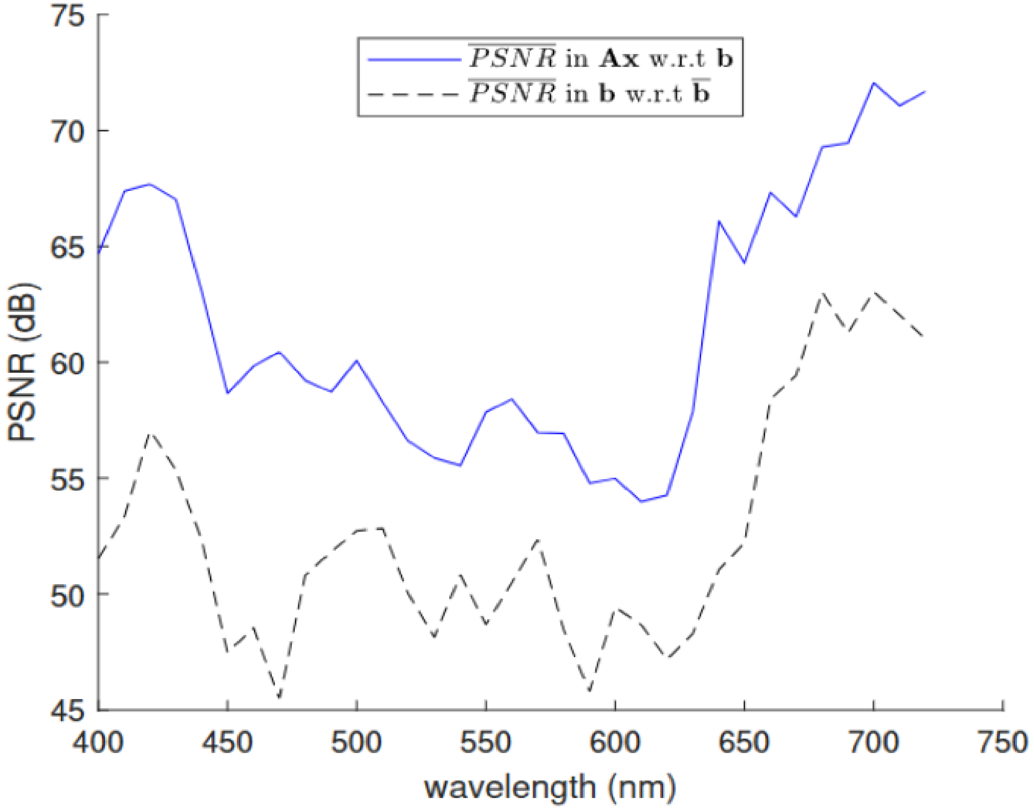

Fig. 13. Mean PSNR for all observers

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Results

Comparing with mean Stiles and Burch 1955 CMFs

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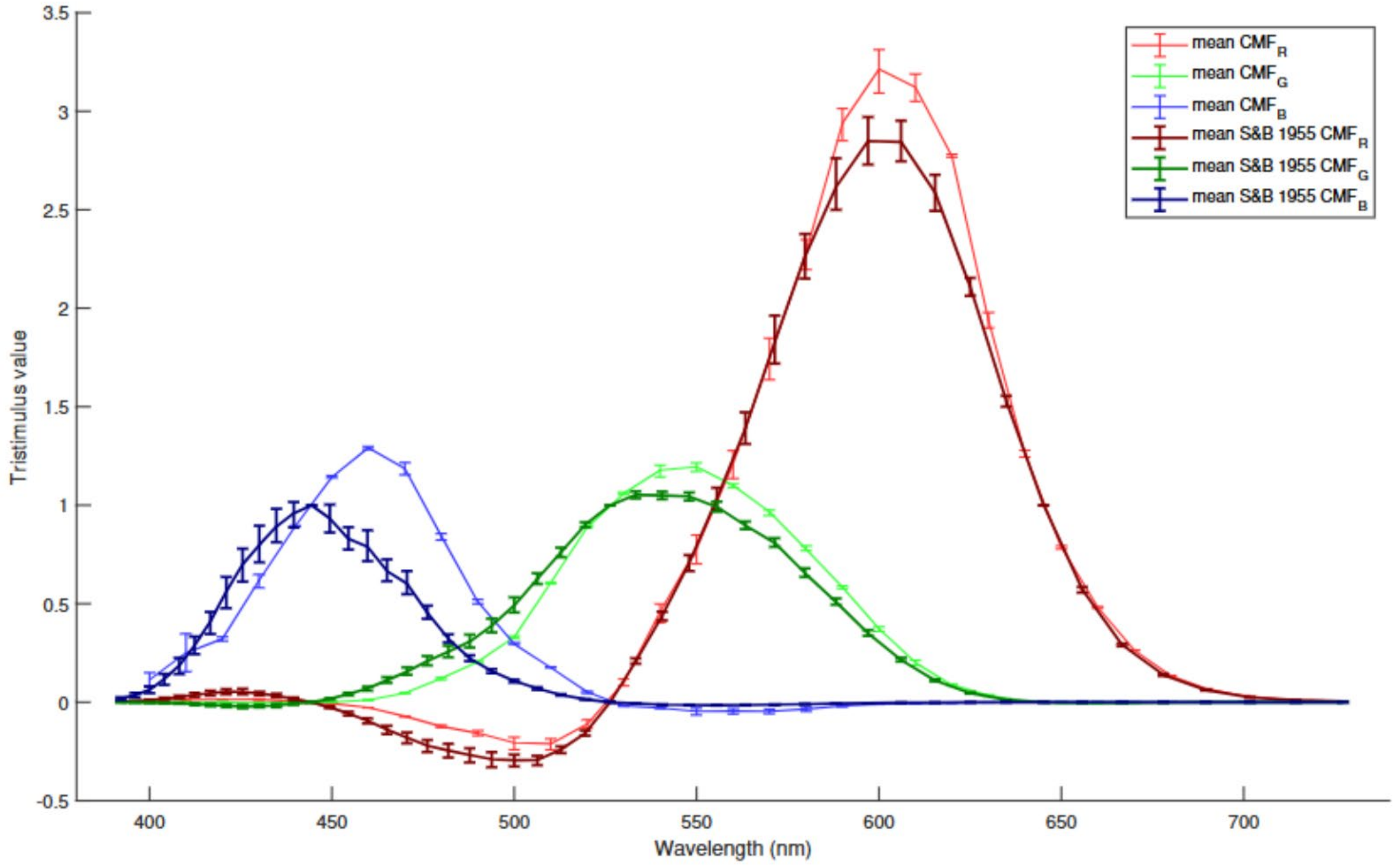

Summary

Colourlab

Colorimeter is simple, compact and relatively cheap.

It can measure intra- and inter-observer differences in individual CMFs with reasonable accuracy.

Further investigations required to investigate discrepancy with Stiles and Burch 1955 CMFs

Experiments are time-consuming.
Faster estimation methods need to be explored.

Apparatus and Method for Measuring Individual Colour-Matching Functions.
Ragoo, Luvin, Ivar Farup, and Jan Henrik Wold. (2024).
Optica Open. Preprint. https://doi.org/10.1364/opticaopen.26235254.v2

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