Internship Report

Simulation of the appearance of historical documents under different light sources

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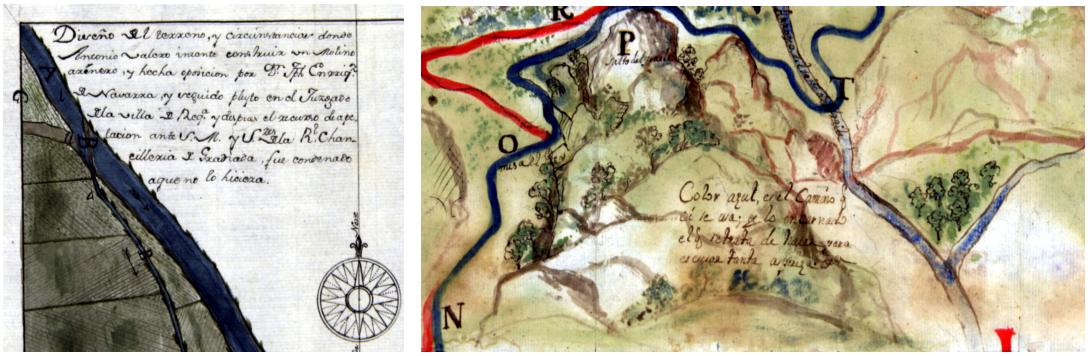
This project aims to replicate the appearance of various documents of historical interest – manuscripts that form the object of the HYPERDOC project of the University of Granada – under various illuminants.

Dataset

The dataset used for the purpose of this project consisted of hyperspectral images (spectral reflectance) of different document sections, acquired using a VNIR camera (López-Baldomero et al., 2024) in the range 400 – 1000 nm.

In Figure 1, we can observe some examples of false-colour representations of manuscript captures, obtained by selecting the 645, 565 and 440 nm wavelengths as R, G and B.



(a) Section 1 (b) Section 2

Figure 1: False-colour images of historical documents

The illuminants used in the simulation are as follows:

- CIE standard illuminants: A, D50, D65, FL1, FL2, FL3, obtained from the CIE Dataset (CIE, 2024);
- Typical Light-Emitting Diode (LED), halogen (TH) and fluorescent (FL) museum light sources available on the website of the research centre of The National Gallery of London (The National Gallery of London, 2024):
  - Philips MASTER LEDspot MV Dimmable: LED - 2700K - 97.00 CRI
  - Sylvania Concord Beacon Muse 2052867 (Narrow): LED - 3000K - 90.00 CRI
  - CREE LRP-38: LED - 2620 K - 93.00 CRI
  - CRS SP12 WW MR16: LED - 3049 K - 96.00 CRI
  - LSI LumeLEX 2040-C4M2-6S: LED - 4000 K - 95.00 CRI
  - GCI Filter Thin-Film Mark 2 on MR16: TH - 2620 K - 93.00 CRI
  - GE EYC 71W MR16: TH - 2709 K - 99.00 CRI
  - Philips 50W MR16: TH - 2703 K - 99.00 CRI
  - GE F40W/AD: FL - 6500 K - 92.00 CRI

  The illuminants were chosen according to the recommendations of Menino Homem, 2016 (p. 7), advising a Colour Rendering Index (CRI) over 90. Their spectral power distributions (SPDs) can be observed in Figures 2 and 3.

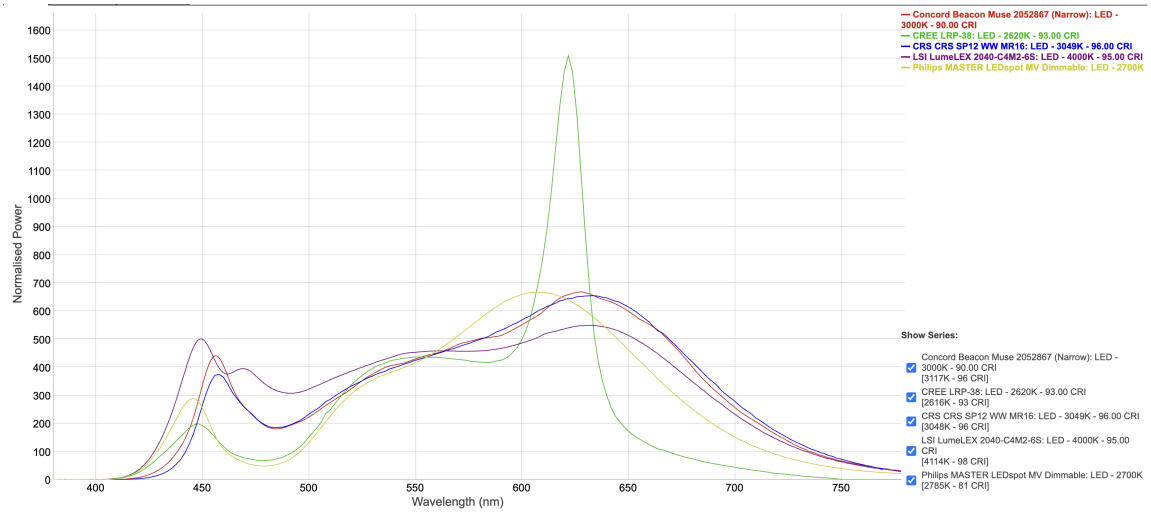


Figure 2: SPDs of the LED illuminants chosen from The National Gallery of London, 2024

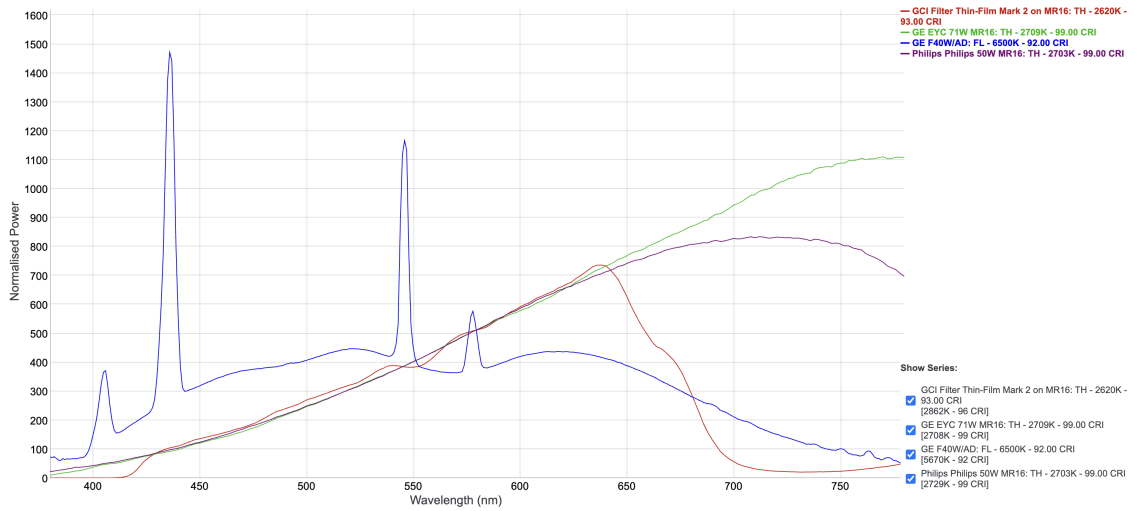


Figure 3: SPDs of the halogen and fluorescent illuminants chosen from The National Gallery of London, 2024

The colour matching functions used were the CIE 1931 2-deg CMFs at 5 nm intervals (CVRL, n.d.). The simulation is carried out within the visible range, namely 400 - 780 nm, at 5 nm intervals. The necessary data interpolation was achieved using the Piece-wise Cubic Hermite Interpolating Polynomial (PCHIP) method.

Preliminary Visualisation

To obtain an initial perspective of the properties of each illuminant and their effect on the documents, we start with a simple simulation in which no chromatic adaptation is applied. This approach involves obtaining the CIE XYZ tristimulus values for each pixel through the matrix multiplication of the reflectances, the spectral power distribution and the colour-matching functions. Afterwards, these values are normalised through the division by the maximum luminance (Y) and then converted to sRGB – this step ensures that the final images are in a format suitable for being displayed on standard monitors.

This conversion follows the IEC 61966-2-1:1999 standard (International Electrotechnical Commission, 1999), where the XYZ values are multiplied by the standard matrix, then the result is cropped to the interval [0, 1] and gamma-corrected. Non-linear compression for the darker region is omitted, as it would lead to a slight over-saturation in the case of warmer light sources.

Some representative results can be observed in Figure 4. Here, we can observe that, in the absence of chromatic adaptation, the simulations are highly dependent on the colour temperature (CCT) of the illumination. In the case of illuminants with a CCT under 3000 K, the representations are increasingly warm – Figures 4e (halogen 2703 K), 4g (LED 3000 K) and 4h (LED 2700 K).

This issue will be further fixed by applying the CIECAM02 chromatic adaptation algorithm in the next section.

(a) D50 standard illuminant

(b) D65 standard illuminant

(c) FL2 standard illuminant

(d) GE F40 fluorescent illuminant

(e) Philips MR16 Halogen

(f) LSI LumeLEX LED

(g) Sylvania Concord LED

(h) Philips MASTER MV LED

Figure 4: Preliminary visualisation under different illuminants

Chromatically-Adapted Simulation

To address the issues observed in the preliminary visualisations, where the appearance of documents varied significantly with the color temperature of the illuminant, we applied chromatic adaptation using the CIECAM02 color appearance model. This model simulates how colors are perceived under different lighting conditions, accounting for human visual adaptation (Moroney et al., 2002).

Here, the reflectance data, CMFs, and SPDs were used to calculate the CIE XYZ tristimulus values for each pixel, both for the document and the reference white under the target illuminant. Then, using the M_{CAT02} matrix (Moroney et al., 2002), the tristimulus values are converted to LMS cone responses and so the chromatic adaptation is applied at cone level. In this step, the function adjusts the LMS values based on the degree of adaptation D, which can range from 0 (no adaptation) to 1 (complete adaptation). The reference white point's LMS values (RwGwBw) are used to scale the input LMS values (RGB), modifying them according to the degree of adaptation:

$$R_c = \left[\frac{Y_w \cdot D}{R_w} + 1 - D\right] \cdot R$$

where:

- R_c is the adapted response in the CIECAM02 color space,
- Y_w is the luminance of the white point,
- D is the degree of adaptation,
- R_w is the response to the white point,
- R is the original response in the CIECAM02 color space (Moroney et al., 2002).

Next, we transform the adapted responses back to XYZ values, which are then converted to sRGB using the standard matrix transformation and gamma correction seen in the previous section.

The chromatically-adapted simulations, shown in Figure 5, demonstrate a significant improvement in color consistency across different illuminants. The perceived colors of the historical documents seem more stable and true-to-life, regardless of the color temperature of the illumination. Hence, this consistency is crucial for accurate visual assessments and comparisons. Here, we can observe an overall slightly greener appearance for the fluorescent light sources (Figures 5c and 5d), and a rather reddish tint for the warmer illuminants (Figures 5e, 5g).

(a) D50 standard illuminant

(b) D65 standard illuminant

(c) FL2 standard illuminant

(d) GE F40 fluorescent illuminant

(e) Philips MR16 Halogen

(f) LSI LumeLEX LED

(g) Sylvania Concord LED

(h) Philips MASTER MV LED

Figure 5: Chromatically-adapted visualisation under different illuminants

Instructions on How to Use the Functions

The simulate_illumination function

The main function – *simulate_illumination* – is used to render the appearance of a sample (a reflectance cube) under the chosen illuminants.

It operates with the following 5 parameters as input:

- *reflectance_cube* – A 3D matrix representing the reflectance data, in the format (height x width x channels)
- *reflectance_range* – A vector specifying the wavelength values for each channel in reflectance_cube (in the format start:step:end, e.g 400:5:1000); this is important so that we can further select the bands that correspond to the visible range; if the *reflectance_range* does not include the visible range (400-780), the function throws an error message.
- *illuminant_names* – A cell array of strings specifying the names of the chosen illuminants (e.g. 'D65', 'FL1', 'LED1'); these are chosen from the list of predefined illuminants (or eventually illuminants added with the *IlluminantOperations.add_illuminant* presented in the following subsection).
- *gamma* – the value used in sRGB gamma correction (nonlinear adjustment applied to pixel values to ensure the brightness levels are perceived correctly displays); commonly used values are 2.2 (standard) and 2.4
- *D* – The degree of adaptation to the illuminant (in the CIECAM02 model), in the range 0-1.

  Chromatic adaptation is the process by which the human visual system adjusts to changes in lighting conditions to preserve the appearance of object colors. Normally, if the light sources are close to "white light", the degree of adaptation is considered close to 1. Considering that the sources of light used to display the documents fall within this category (they mimic natural light, with slight variations; for example, some of the sources of light used here were rather warmer, but with a good Colour Rendering Index), a recommended degree of adaptation that can be used would be 0.9. If, however, the source of light is close to monochromatic, the degree of adaptation should be reduced.

The function provides as output a structure containing the simulated results under the chosen illuminants:

- *simulations.simple_illum*: the sRGB images (in the range [0,1]) obtained through simple visualisation under each illuminant, identifiable by the illuminant names
- *simulations.adapted_images*: the sRGB images (in the range [0,1]) with chromatic adaptation obtained using CIECAM02, identifiable by the illuminant names

The IlluminantOperations Class

The IlluminantOperations class contains 4 static methods that perform CRUD operations (Create, Retrieve, Update and Delete) on the illuminants_table.mat file, which represents the local database of illuminant data. Its functions can be accessed as: IlluminantOperations.function_name, for example: IlluminantOperations.add_illuminant(name, spd).

- `load_illuminants_table()`: Loads the illuminants table stored in `illuminants_table.mat` into memory. This function allows access to all the illuminants and their spectral power distributions (SPDs) stored in the file.
- `add_illuminant(name, spd)`: Adds a new illuminant to the table with the specified `name` and spectral power distribution (`spd`). Before adding, it checks if an illuminant with the same `name` already exists to prevent duplicates. If no duplicates are found, the new illuminant is appended to the existing table and saved back to `illuminants_table.mat`. The spd to be added should be an n x 1 matrix.
- `get_illuminant_by_name(name)`: Retrieves the spectral power distribution (SPD) of an illuminant specified by its `name` from the table. It searches for the illuminant based on the `name` and returns its SPD if found. If the illuminant is not found in the table, an error is raised indicating its absence.
- `update_illuminant(name, new_spd)`: Updates the spectral power distribution (SPD) of an existing illuminant specified by its `name` in the table. It first checks if the illuminant exists by searching for its `name`. If found, the SPD of the illuminant is updated with `new_spd` and the modified table is saved back to `illuminants_table.mat`. If the illuminant is not found, an error is sent.
- `delete_illuminant(name)`: Deletes an illuminant from the table based on its `name`. It searches for the illuminant by `name` and removes its entry from the table if found. The updated table excluding the deleted illuminant is then saved back to `illuminants_table.mat`. If the illuminant with the specified `name` does not exist, the function gives an error message.

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López-Baldomero, A. B. et al. (Apr. 2024). *Hyperspectral Database of Synthetic Historical Inks*. URL: https://colorimaginglab.ugr.es/pages/hyperdoc/database.

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